Residential Microenvironmental and Personal Sampling Project for Exposure Classification

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Prepared for the California Air Resources Board

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ABSTRACT

This project sought to gather exposure assessment information for improved modeling of human air pollution exposures. Air monitors were deployed during 247 visits (1126 initial visits, 121 second visits) to homes across four Southern California communities. Home selection was based on concurrent participation in a cross-sectional air pollution health effects study, air conditioning type, and community location. Measurements were performed between February and November 1994, to observe potential differences in seasonal patterns of home operation. Sampling included administration of three survey questionnaires to document housing and human activity factors of potential importance and simultaneous indoor/outdoor air sample collection over a 24hr period. Measurements included ozone, particulate matter (PM_{10} and $PM_{2,5}$), formaldehyde, and house air exchange rate in a variable number of homes. A twelve-home pilot study also provided two-week integrated data about indoor/outdoor levels of airborne acids and fine particle chemistry.

Indoor ozone was typically low (median of 5.6 ppb); the median outdoor ozone concentration was 34 ppb. The indoor/outdoor (I/O) ratio (median value of 0.20) displayed a distinct seasonality, with the ratio increasing during summer months. Indoor PM_{2.5} measurements (median of 13.7 μ g/m³) tended to be higher than outdoor levels (median outdoor PM_{2.5} of 10.7 μ g/m³, median I/O PM_{2.5} ratio of 1.10), reflecting the presence of indoor sources. A strong seasonality of either PM_{2.5}, or the PM_{2.5}, I/O ratio was not observed, but this may be due more to the time period of field observations (late June through November only) than to the lack of a seasonal PM relationship across the year. Median observed PM₁₀ levels were 32.9 μ g/m³ indoors and 29 μ g/m³ outdoors, with a median I/O ratio of 1.05. Several homes were observed with indoor levels exceeding 100 μ g/m³. No strong PM₁₀ seasonality was observed, which may be an effect of the sampling period. Indoor formaldehyde levels were low (median value of 10 μ g/m³), but were higher than observed outdoor levels (median of 3.2 μ g/m³). No formaldehyde seasonality was observed. Median air exchange rates (AER) were calculated to be 0.7 hr⁻¹, using a corrected home volume method that accounted for space-occupying objects in the home (this approach tended to increase observed AER estimates by about 10%). AER tended to be lower

during the spring and fall than during the summer. Summertime AERs were also more variable.

Comparison of community fixed-site station data to measurements made immediately outside the study homes revealed an acceptable predictive relationship for ozone, but a poor relationship for PM, with lower PM levels reported at the homes than observed at the stations. Models to predict indoor levels for ozone and PM had moderate, but unimpressive, predictive power (R^2 of 0.38 to 0.67). Key model variables for predicting indoor ozone included ambient ozone levels and the length of time home windows were open. For PM₁₀, model variables of importance included ambient PM₁₀ levels and an indicator variable for cigarette smoking. Ambient PM_{2.5} levels, the amount of time for stove use, and an indicator for the home being a two-bedroom residence, were shown to be important for the indoor PM_{2.5} model. The pilot airborne acid study succeeded in demonstrating feasibility of instrument deployment and the credibility of sample collection, and suggested the presence of elevated levels of organic acids in homes.

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[USC=University of Southern California, IES=Integrated Environmental Services, ADI=Aerosol Dynamics Inc, STI= Sonoma Technology Inc, LAREI= Los Amigos Research and Education Institute, HSPH= Harvard School of Public Health, SCAQMD= South Coast Air Quality Management District] "The statements and conclusions in this report are those of the contractor and not necessarily those of the California Air Resources Board. The mention of commercial products, their source or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products."

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0. Executive Summary

0.1 Introduction

This project was designed to advance the fields of exposure assessment and air pollution health effects research through direct collection of field data and subsequent modeling of the observed results.

The goal of this project was to gather exposure assessment information for use in improved modeling of human air pollution exposures. This was accomplished by collecting air sampling information during 247 visits (126 initial visits, and 121 second visits) to 126 homes of a sub-group of children participating in a cross-sectional air pollution health effects study (California Air Resources Board Contract #A033-186). Measurements made in the course of the home sampling study included the determination of indoor/outdoor ozone, indoor/outdoor respirable particulate matter (both PM_{10} and $PM_{2.5}$), indoor formaldehyde, house air exchange rates, and some limited pilot information regarding indoor/outdoor levels of airborne acids.

0.1.1 Objectives

The specific objectives of the project were:

(1) to assess the applicability of the Regional Human Exposure (REHEX) model, and modify it, as appropriate, to address large-scale epidemiologic investigations;

(2) to validate the REHEX model using collected exposure data;

(3) to compare exposure estimates derived from interpolation of community monitoring stations with those derived from microenvironmental and personal sampling information collected in the course of the study;

(4) to expand the existing data base on current levels of indoor air contaminants;

(5) to establish the relationship between indoor/outdoor ozone ratios, housing characteristics, and air exchange rates in a sub-set of study homes;

(6) to construct a reliable and cost-effective long-term sampler for indoor/outdoor measurement of fine particles and acids.

The absence of a validated acceptable personal ozone sampler for use in the study precluded complete achievement of all six project objectives. However, significant progress was made towards meeting those objectives requiring a validated personal ozone sampler. Project objectives relying on personal exposure information will be addressed in Phase III of Children's Health Study (California Air Resources Board [CARB] Contract #A033-186).

0.1.2 Design Approach

The housing stock chosen for study was selected from among the several thousand homes of subjects participating in the CARB Children's Health Study. In four of the twelve Southern California communities in which the Children's Health Study was being performed (San Dimas, Riverside/Mira Loma, Lancaster, and Lake Gregory/Lake Arrowhead), residences were chosen for participation in the residential study.

The study design primarily emphasized seasons and locations with high ozone, and also collected information in areas with historically elevated particulate matter (PM). Homes from the community of San Dimas were selected due to their location in an area characterized by historically high ambient ozone concentrations. Homes from the Mira Loma/Riverside area were selected for their location in an area high in PM and ozone. Homes in the community of Lancaster, a high desert community north of Los Angeles, were chosen to take advantage of sampling in a community with a large number of swamp-cooled homes in an area of moderate ambient ozone and PM. Homes in Lake Gregory/Lake Arrowhead were selected to provide housing stock from an area high in ambient ozone and prone to more severe seasonal weather (snow, sleet, and rain) than that typically seen in most of the other study communities (which might also be reflected in differences in housing tightness and operation).

Within a given community, homes were selected based on preliminary survey data (available from a baseline questionnaire collected in the performance of another CARB-supported project, the USC Children's Health Study - CARB #A033-186) which provided information regarding the presence of home air conditioning. Homes without air conditioning were also sampled in each of the four target communities. An additional effort was mounted to recruit as

many swamp-cooled homes as possible, based on the hypothesis that use of an evaporative air conditioner (such as a swamp cooler) would lead to higher volumes of outside air being drawn into the home, and higher indoor levels of outdoor pollutants.

The study sampling goal was to perform measurements in 150 study homes, sampled in each of two seasons to assess possible differences in seasonal home operation, human activities, and pollutant levels. Approximately equal numbers of homes were to be recruited from each of the four study communities, with an additional twenty-five swamp-cooled homes chosen from across the study communities.

Three types of questionnaires were collected for study use, and five types of air sampling measurements were made in the study home population, according to a prearranged sampling assignment that maximized limited sampling resources. All three questionnaires were collected for all participating study homes. A Baseline questionnaire, collected during recruitment and enrollment of students participating in the CARB-supported Children's Health Study, was used to characterize the potential housing stock for potential residential study eligibility. A Technician survey was completed by field staff during a walk-through visit in the study home, to objectively report on the housing characteristics. A Follow-up survey was completed during a resident interview performed by field staff following home sampling, to document actual home operation and the occurrence of other relevant activities during sampling.

Sampling of ozone levels indoors and immediately outside of study homes for a continuous twenty-four hour (24hr) sampling period was accomplished using a controlled-flow Timed Exposure Diffusion (TED) sampler (developed and validated in the Children's Health Study). The TED sampler exposed a commercially available nitrite-saturated filter, which oxidized in the presence of ozone to form a stable nitrate on the filter. Filters were then analyzed in the laboratory using ion chromatography. Two TED samplers were purchased for use in the project, and 28 additional samplers were loaned to the residential field team by the Children's Health Study exposure assessment group.

To gather limited information about continuous ozone trends inside and immediately outside of study homes and to collect some quality control data on the performance of the TED samplers, two commercial ultra-violet photometers interfaced to a computerized data-logger were installed in eight of the study homes for 24hr sampling periods.

Particle sampling was performed inside and immediately outside the sampling homes using occupational hygiene type sampling pumps connected to Personal Exposure Monitors (PEMs). PM samples were timed to coincide with the other air monitoring efforts in the home (that is, all samples were collected during a given visit in any specific home over the same 24hr sampling period). The PEMs were single-stage impactors and were used to obtain samples of $PM_{2.5}$ and PM_{10} on a filter substrate that was subsequently weighed and archived at the supporting laboratory (at the Los Amigos Research and Education Institute) for possible future analyses. The sampling substrate used during the first few months of routine field operations was a glass fiber filter, but this was turned out to be a poor sampling choice. Although the use of glass fiber filters with the PEM was in conformance with manufacturer's recommendations, it was contrary to the project's standard operating procedures. The use of glass fiber filters resulted in a large number of sample filters being sheared by the PEM sealing edge, leading to unreliable filter mass determinations. A teflon filter with a poly-olefinic ring was used to address this problem, and this approach dramatically reduced filter shearing and questions of sampling validity (the results reported herein reflect measurements made using the teflon filter media only).

Formaldehyde samples (n=99) were collected in a subset of the sampling homes using a 2,4-dinitrophenylhydrazine (DNPH) saturated cartridge and a flow-controlled sampling pump. Samples were collected over a 24hr period. A small number of outdoor samples (n=18) were also collected, over the same sampling period, to assess ambient formaldehyde levels. All sample cartridges were prepared and analyzed in a commercial service laboratory (AtmAA) using high performance liquid chromatography (HPLC).

Perfluorocarbon tracer releases, to determine air exchange rates, were performed in 86 participating homes. Tracer gas sources were placed in the study home at least 24 hours in

advance of actual sampling to allow for dispersal of the tracer gas throughout the home. Carbon capillary adsorption tubes (CATs) were deployed in the home for a 24hr sampling period to collect the sample, and the CATs were returned to a supporting laboratory for analysis by gas chromatography. Sources, CATs, handling procedures, and analyses were provided by the supporting laboratory (Harvard School of Public Health).

As a pilot sampling study to demonstrate technical feasibility, a novel two-week sampler (TWS) was fabricated and placed inside and immediately outside 12 study homes to collect information about gas and particle phase acids and fine particle ($PM_{2.5}$) chemistry. The TWS was designed to provide fourteen-day integrated measurements of ambient vapor phase nitric and hydrochloric acids, $PM_{2.5}$ mass and chemistry for inorganic ions of interest (sulfate, nitrate, and ammonium), and organic acids (formic and acetic). Four TWS units (two for indoor sampling and two for outdoor sampling) were assembled and used in the project.

Ambient monitoring data was collected during the sampling project at community network monitoring stations operated by exposure assessment personnel of the Children's Health Study, or by personnel of the South Coast Air Quality Monitoring District. Ambient ozone data was continuously collected at the fixed-site station by commercial instrumentation based on ultraviolet photometry. Particulate matter was measured hourly, using commercial Tapered Element Oscillating Microbalance (TEOM) units. This data was then made available to residential study investigators for modeling purposes.

0.2 Results

Full-scale study field operations were initiated in February 1994 and continued into November 1994. During that time period, 247 home visits (126 first-time visits and 121 return visits) were completed. The goal of 300 home visits was not achieved due to limitations associated with instrumentation, personnel, and residential scheduling. Of the homes that participated in the project, 29 were located in Lake Gregory, 37 were in Lancaster, 36 were in Riverside/Mira Loma, and 24 were in San Dimas. Of these 126 homes, 29 were documented as having evaporative air cooling (or "swamp cooler" type) systems.

0.2.1 Residential Characterization By Survey

Information from the Baseline Survey questionnaire was available for 125 homes. Almost 90% of study homes were single-family detached residences, and over 70% of the study homes had three or four bedrooms. More older homes were studied in Riverside/Mira Loma and San Dimas than in Lake Gregory and Lancaster. The average study home in Riverside/Mira Loma was smaller (in terms of measured home volume) than in other communities. Of the homes studied, three times as many homes had concrete slab foundations than raised floors with a crawlspace, except in Lake Gregory, where the ratio was reversed.

In Lancaster, nearly every home reported the presence of air conditioning, while in Lake Gregory, virtually no home had an air conditioner. Central or room air conditioning systems were present in over 50% of the homes in Lancaster, Riverside/Mira Loma, and San Dimas. Swamp coolers were reported in a substantial number of study homes (29% in Lancaster, 25% in Riverside/Mira Loma, and 25% in San Dimas), reflecting the preferential recruitment effort directed towards swamp-cooled homes.

The reported presence of a resident smoker in the study home varied from 11% in Riverside/Mira Loma to 22% in San Dimas. However, accounting for non-resident smokers regularly present in the home roughly equalized smoking distributions across communities (21% in Lake Gregory, 27% in Lancaster, 19% in Riverside/Mira Loma, 26% in San Dimas).

No technician-observed differences in home dust control were reported except in Riverside/Mira Loma, where proportionally, twice as many homes as elsewhere (25% of the Riverside/Mira Loma homes compared to 9-14% in the other three communities) were subjectively rated (by field personnel) as having excellent cleaning.

Air conditioner use, during 24hr home sampling, was reported in almost a third of the sampling studies (72/246), and a similar number of homes reported using portable and ceiling fans (69/246 and 76/246, respectively). The use of home heating was reported during sampling

in about a fourth of the study homes. When an air handling unit was used (such as heating, air conditioning, or fans), duration of use was typically at least three to five hours.

Over a third of the study homes reported having a window open during the 24hr sampling period, and over 85% of those homes reported having windows open for more than a few minutes during sampling. Approximately 20% of study homes reported leaving windows open for more than 3 hours during the afternoon of the sampling day, except in San Dimas, where only 6% opened their windows during the afternoon of the sampling day.

Vacuuming and dusting was performed during sampling in about a third of the study homes. Cigarette smoking during the sampling period was reported about half as often in Lake Gregory as in other communities (less than 10% of the study visits, compared to 20% in other communities), but other sources of smoke in the home (such as from incense or burning candles) were equally distributed across the four study communities in about 16% of the homes (40/246 study visits).

0.2.2 Exposure Assessment

0.2.2.1 Ozone

A total of 481 valid residential ozone measurements (241 indoor, 240 outdoor) were reported. Indoor ozone levels were almost always below those observed outdoors during the same time frame, reflecting the apparent absence of any operating indoor sources. The median observed 24hr indoor ozone level was 6 ppb for the 241 measurements reported, with an interquartile range from 2 to 16 ppb O_3 . Outdoor levels were somewhat higher (median value of 34.2 ppb, with an inter-quartile range from 22.8 to 50.6 ppb O_3).

Observed 24hr mean ozone concentrations ranged from 10 ppb in San Dimas homes to 17 ppb in Lake Gregory homes, while mean 24hr outdoor levels varied from 0.027 ppm in San Dimas to 0.045 ppm in Lake Gregory. When the collected data was reviewed on the basis of reported air conditioning type, homes with central or room air conditioning had lower 24hr average ozone levels than others (9 ppb, compared to 16). However, confounding considerations,

such as the skewed distribution of air conditioning types in some communities, suggest that caution should be exercised in interpreting this data.

A seasonal ozone pattern was observed, with levels higher during the summer months. Indoor/outdoor ozone ratios also increased during the summer months; this is the apparent result of residents opening windows to provide natural ventilation rather than using air conditioning.

Continuous ozone information was also collected inside and outdoors of five homes, using commercial ultra-violet photometers. In one of these homes, ozone levels exceeded the ambient air quality standard (90 ppb for one hour) for several hours. In the remaining four homes, indoor values were much lower than outside levels, except for some periods in the late afternoon or evening. The effects of window opening and fan cycling from home air conditioning were apparent from the rapid changes in indoor ozone levels observed in some of the continuous tracings.

0.2.2.2 Particulate Matter

0.2.2.2.1 PM₁₀

Valid teflon filter-based PM_{10} measurements were made in or around 90 homes. Measured indoor PM_{10} levels tended to be higher than those observed outdoors (median indoor concentration of 32.9 µg/m³ compared to 29 µg/m³ outdoors, with a median indoor/outdoor ratio of 1.05). Indoor PM_{10} inter-quartile percentile concentrations averaged ranged from 24 µg/m³ to 47 µg/m³. In a few homes, PM_{10} levels approaching 150 to 300 µg/m³ were observed. A maximum outdoor PM_{10} level of 141 µg/m³ was observed, with the inter-quartile range from 18 µg/m³ to 44 µg/m³.

Measured PM_{10} levels tended to be higher in the Riverside/Mira Loma study homes than in the other communities. This is in conformance with previous historical monitoring information, which has identified the Riverside/Mira Loma area as one the highest observed locations of ambient PM_{10} in the United States. Review of the data also suggested that measurements made in the Lake Gregory homes were lower than in the other study communities, but this was somewhat obscured by a few extreme outlier samples in homes in Lancaster and Riverside/Mira Loma, making objective determination of a small data set increasingly difficult. It was not possible to draw summary conclusions from the PM_{10} data as a function of reported air conditioning type, due to the presence of extremely large values among a small number of data points.

No strong PM_{10} seasonality relationship was detected, but this is more likely due to the period of field operations performance (summer to fall for teflon-filter based sampling, with no winter sampling when elevated PM levels might be expected) than to actual annual trends.

0.2.2.2.2 PM_{2.5}

Valid teflon-filter based $PM_{2.5}$ measurements were made in 67 homes. Compared to concurrent outdoor measurements, indoor $PM_{2.5}$ levels were generally elevated (median indoor concentration of 13.7 µg/m³, compared to 10.7 µg/m³ for outdoor levels). For the 61 concurrent indoor/outdoor $PM_{2.5}$ measurements made, a median ratio of 1.10 was observed (with an interquartile range from 0.84 to 1.68).

As was the case for PM_{10} , homes in the Riverside/Mira Loma area reported the highest average indoor and outdoor $PM_{2.5}$ levels measured (with observed 24hr $PM_{2.5}$ concentrations of 33 µg/m³, compared to 10 to 20 µg/m³ elsewhere). On average, homes in Lake Gregory tended to have the lowest reported $PM_{2.5}$ levels, but there was a significant amount of data overlap and relatively few data points.

No definitive conclusions could be drawn from a review of the $PM_{2.5}$ data, divided by reported air conditioning type. The data suggested a trend towards increasing indoor $PM_{2.5}$ from homes with no air conditioning to central to swamp cooling (16 to 20 to 25 µg/m³, respectively), but sample sizes were small and standard deviations were large.

Seasonal patterns for $PM_{2.5}$ were no more convincing than for PM_{10} . The collected data

suggested that some elevated indoor levels might have occurred during the fall, but this trend was limited and should be considered speculative based on the available evidence (due to problems with filter media during PM sampling, data is reported here for the summer and fall seasons only, thus limiting assessment of seasonal trends).

0.2.2.2.3 Collocated PM_{2.5} and PM₁₀ Sampling

Collocated $PM_{2.5}$ and PM_{10} sampling was performed during 23 of the residential study sampling visits . Values ranged from 2 to 77 μ g/m³ for $PM_{2.5}$ and 5 to 114 μ g/m³ for PM_{10} outside the study homes and from 4 to 107 μ g/m³ for $PM_{2.5}$ and 2 to 162 μ g/m³ PM_{10} inside the residences.

The correlation value for collocated $PM_{2.5}$ and PM_{10} collected outside these homes was 0.86. As in other studies, indoor smoking was an important influence on indoor PM levels. In those homes where smoking occurred during collocated sampling (n=7), observed indoor levels of $PM_{2.5}$ and PM_{10} were strongly related, with a correlation value of 0.77 observed. In homes in which no smoking was reported, the relationship between collocated $PM_{2.5}$ and PM_{10} was much lower ($R^2 = 0.40$). However, this data represents a small number of samples and may have been driven by single extreme points, so care should be taken to avoid over-interpretation.

0.2.2.3 Formaldehyde

Indoor sources of formaldehyde were low in the 99 homes measured (median of 10.1 μ g/m³, with an inter-quartile range from 6.5 to 15.2 μ g/m³). Outdoor levels were observed in the 1 to 10 μ g/m³ range, with a median of 3.2 μ g/m³ (inter-quartile range from 1.7 μ g/m³ to 4.1 μ g/m³) for the 18 outdoor measurements made. Indoor levels of formaldehyde were generally higher than concurrent outdoor levels, with an observed median indoor/outdoor ratio of 3.75, and an inter-quartile range from 1.98 to 7.38. No seasonal pattern was evident in the collected formaldehyde data.

The indoor formaldehyde data suggested that the average home in the Riverside/Mira Loma area might have slightly higher 24hr levels than elsewhere (mean 24hr value of 15 μ g/m³, compared to 10 μ g/m³ in the other communities), but sample sizes were on the order of 20 to 25

data points in each community. Very few outdoor samples were collected as part of the study, so no conclusions were formed regarding outdoor formaldehyde levels, as a function of community. When divided by reported air conditioning type, average 24hr formaldehyde levels were in the 9 to 13 μ g/m³ range, without any clear differences identified.

0.2.2.4 Air Exchange Rates

A total of 161 air exchange rate (AER) measurements were reported for the 86 homes in which measurements were made. Both the traditional approach (measuring wall-to-wall volume without accounting for furniture and other space-occupying objects) and an exploratory approach, in which the volume of space-occupying objects were estimated and subtracted from the exchangeable volume, were used. Use of the corrected volume approach tended to increase estimates of AER by about 10%, and appeared to be relatively constant from home to home across the housing stock evaluated in this project.

A median AER value of 0.7 hr^{-1} (with an inter-quartile range from 0.4 to 1.1 hr⁻¹) was observed among the homes sampled, using the corrected volume approach (for comparative purposes, the traditional approach revealed a median AER of 0.7 hr^{-1}). Due to the limitations of the AER method as deployed (including home equilibration of sources and sampling for 24hr), there was greater confidence in reported values less than 1 hr⁻¹.

The available data suggested that, by community, measured AERs might be higher in Lake Gregory than in the other study areas (0.9 hr⁻¹, compared to values around 0.7 hr⁻¹). Homes with swamp cooling had higher AERs than homes with central or no air conditioning (1.2 hr⁻¹, compared to 0.6 and 0.9 hr⁻¹, respectively). This makes intuitive sense, given the operational characteristics of swamp cooling units.

The data collected in this study suggested that AERs were lower in spring and fall, compared to the summer period. Summertime also was characterized by a more variable pattern of air exchange. A possible explanation for this observation is the significant use of natural ventilation (opening windows) and the selective use of home air conditioning, except during the

hottest summer days. The cost associated with the operation of home air conditioning was frequently mentioned by residents, during survey interviews and by field technician anecdotal reports, as a factor of importance in this observed behavior.

0.2.2.5 Pilot Assessment of Acids Using Two-Week-Samplers

Two-week sampler (TWS) data were collected in twelve homes, distributed across all of the four sampling communities, between August and November 1994. Observed nitric acid (HNO₃) concentrations ranged from 0.5-13 μ g/m³, with indoor concentrations typically less than half of the observed outdoor concentrations. Hydrochloric acid (HCl) levels in and around the homes were less than 3 μ g/m³ and erratic, with some homes having indoor measurements higher than outdoors, and others vice versa.

Observed $PM_{2.5}$ mass data varied from a few $\mu g/m^3$ to over 30 $\mu g/m^3$ indoors, and over a slightly smaller range outdoors. Sulfate, nitrate, and ammonium levels reflected seasonal PM trends (higher in summer, lower in the fall). Sulfate levels were similar indoors and outdoors, and ranged from 0-3 $\mu g/m^3$ indoors and 1-4 $\mu g/m^3$ outdoors. Observed NO₃⁻ levels varied from about 1 to 12 ug/m³, with about half of the homes reporting higher indoor levels than concurrent outdoor measurements. Ammonium ion levels varied from less than 0.5 ug/m³ to almost 5 ug/m³, with outdoor levels typically equal to or exceeding indoor levels.

Indoor concentrations of formic and acetic acids were 2-10 times higher than their respective outdoor levels, with appreciable home-to-home variability. The highest observed indoor acetic acid measurement (69.9 μ g/m³) was collected in a mobile home in Riverside/Mira Loma, but values close to this were also observed in more conventional single family residences in San Dimas and Lancaster. The highest observation of indoor formic acid was found in San Dimas (52.9 μ g/m³), almost twice as high as the next highest observation.

0.2.3 Modeling Results

0.2.3.1 Comparison of Residential Outdoor and Community Monitoring Data

The collected residential sampling data was compared to ambient data collected at the

respective community monitoring stations during the time of sampling. Ozone outdoor residential concentrations correlated reasonably well in the communities of San Dimas, Riverside/Mira Loma, and Lancaster (R^2 of 0.60 to 0.80). Mean observed residential ozone concentrations were seventeen and twelve percent lower than the corresponding community monitor concentrations in San Dimas and Riverside/Mira Loma, respectively, and essentially identical in Lancaster. In Lake Gregory, however, the correlation results were less satisfactory (R^2 of 0.39 to 0.43), raising potential concern over just how representative the Lake Gregory or Lake Arrowhead station monitoring sites actually were of the residential exposures in the surrounding community.

Particulate matter (PM) outdoor residential concentrations did not correlate as well as ozone (R^2 for PM_{10} data ranging from 0.01 to 0.49 across study communities). PM_{10} levels measured immediately outside of study homes were twenty-nine to fifty-six percent lower in mean concentration than the corresponding community monitor concentrations in their respective communities. Interpolation among community monitors from nearby reporting stations did not result in a significant improvement in the correlation between the residence and community monitor concentrations.

Comparisons of residential $PM_{2.5}$ concentrations to estimated $PM_{2.5}$ levels at the community monitors (since $PM_{2.5}$ was not routinely measured at regulatory stations) were similar to those for PM_{10} . Mean residential $PM_{2.5}$ levels were twenty-seven to forty-one percent lower than estimated community monitor values. A moderate correlation ($R^2 = 0.36$ to 0.54) between residential $PM_{2.5}$ and station data from San Dimas, Mira Loma, Rubidoux, and Lake Arrowhead was observed, but little correlation (0.01 to 0.07) was found between measured residential and estimated station $PM_{2.5}$ concentrations in Lancaster and Riverside.

The lower mean residential PM concentrations observed were most likely related to differences in PM monitor siting criteria at regulatory agency sites (compared to those used for sampling around private homes) and/or to differences in sampling instrumentation (TEOMs used at community stations compared to single-stage impactors at the homes).

Responses to the residential surveys were reviewed for potential use in developing a model to predict residential concentrations from observed ambient concentrations. None of the survey responses evaluated were found to increase the predictability of the model.

0.2.3.2 Modeling Indoor Levels of Pollutants

The collected survey and monitoring information were considered as potential explanatory variables in linear models to predict indoor levels of ozone, PM_{10} , and $PM_{2.5}$. Due to the small number of paired indoor/outdoor formaldehyde samples (n=18), no modeling of indoor formaldehyde was attempted. Several models were evaluated for each pollutant of interest, in order to identify the most promising model exploiting the collected data.

The results indicated that indoor concentrations of ozone were associated with outdoor ozone levels (measured at the community monitoring station) and the duration of time that windows were left open in the home; the coefficient of determination (R^2) for this two-variable model was 0.38. The inclusion of the next several most important explanatory variables (based on these analyses) slightly improved the predictive capability of the model (R^2 of 0.49, for a six-variable model including the above variables and temperature, refrigerant and evaporative air conditioning, and mold odor).

Use of ozone measurement data collected immediately outside the home to predict indoor levels, rather than using community station-based data, only improved the model's predictive capabilities slightly (from an R^2 of 0.52 to 0.61). Overall, the information collected was judged adequate to predict indoor levels on a given day with modest accuracy, based on knowledge of that day's household use.

For PM_{10} , the most important factor in determining indoor levels was smoking; a twovariable model including PM_{10} measured at the community station and a categorical variable indicating the number of cigarettes smoked was found to have an R² of 0.40. The addition of the next four variables of model importance only improved the R² to 0.49. Smoking more than ten cigarettes in the home during the 24hr sampling period was significantly associated (p<0.05) with a PM_{10} increase of 67 $\mu g/m^3$.

In non-smoking residences, the best model found for predicting indoor levels of PM_{10} included station level, duration of ceiling fan use, the existence of mold odors, the existence of other odors, other smoke and cooking in the home, a categorical variable for a two-bedroom home, the presence of a central refrigerating recirculating air conditioner (CRRAC), and an interaction term between station PM_{10} level and the CRRAC. This model had an R² of 0.55.

Use of PM_{10} data collected immediately outside the home instead of community station PM_{10} did not improve the modeling results (R² of 0.47 using PM_{10} data immediately outside the home, compared to an R² of 0.55 using station PM_{10} data).

For $PM_{2.5}$, modeling efforts were restricted to only non-smoking homes, because there were only 17 cases where smoking had occurred in the home during sampling (judged to be an insufficient number for modeling). A model including ambient $PM_{2.5}$, the number of minutes of stove use, and an indicator for being a two-bedroom residence was found to have an R² of 0.64. However, the model selection may have been somewhat unstable due to small sampling sizes (based on 47 visits in non-smoking homes). Use of $PM_{2.5}$, data collected immediately outside the home instead of at the community station, did not markedly improve modeling results (R² increased from 0.64 to 0.67).

0.2.3.3 Improvements in REHEX (REHEX-III)

One of the objectives of this study was to improve the Regional Human Exposure (REHEX) model, through analysis of the residential data and through model evaluation using personal monitoring data. Although no personal monitoring data was collected in this study (due to the lack of an acceptable sampler for personal sampling), the data collected in the current project are useful for improving model estimates of indoor residential concentrations.

Using the collected data, models were developed to predict indoor ozone and indoor PM_{10} . These models were of the following form: $[O_3]_{indoor} = -14.43 + 0.27[[O_3]_{ambient} + 1.13[T]_{24hr min} + 3.99[Built before 1960] + 10.74[AC Equipment] - 1.05[T]_{24hr min} [AC Equipment]]$

 $[PM_{10}]_{indoor} = 22.04 + 0.19[PM_{10}]_{ambient} + 11.11[Odor of Mold] + 5.68[Pets] - 6.04[Heat Duct in Interior Closet or Wall]$

and used variables not dependent on day-specific operating parameters of individual homes (such as the number of hours windows are left open, or whether an air conditioner is being used).

However, there are some important limitations to the proposed use of these improvements for REHEX. First, REHEX requires 1hr ozone averages for model input, and the models derived here were based on 24hr average concentrations; the accuracy and applicability of the indoor models for shorter averaging times is unknown at this time. For PM_{10} , the model was based on data from non-smoking homes only, since there were too few homes with active smoking took place during sampling to provide useful information for model development. The continued improvement and evaluation of REHEX-III will be a portion of the objectives in the Children's Health Study, under a separate CARB contract.

0.3 Achievement of Study Objectives

This project characterized a sub-set of Southern California homes with regard to housing characteristics, pollutant levels, and both community/residential and indoor/outdoor relationships of several outdoor pollutants (ozone, PM_{10} , $PM_{2.5}$, and formaldehyde). The status of the study objectives are as follows:

(Objective #1), to assess the applicability of the Regional Human Exposure (REHEX) model, and modify it, as appropriate, to address large-scale epidemiologic investigations -

This objective was not achieved, since a validated personal ozone monitor was not identified for use in providing personal exposure information, which is a critical component of data input for REHEX modeling (as described in the previous section, improvements in REHEX will be one of the efforts to be performed in the Children's Health Study, a separate but complementary research effort currently underway under CARB support);

(Objective #2), to validate the REHEX model using collected exposure data -

This objective was not achieved, since a validated personal ozone monitor was not identified for use in providing personal exposure information, which is a critical component of data input for REHEX modeling (as previously described, validation of the revised REHEX model will be one of the efforts to be performed in the Children's Health Study, a separate but complementary research effort currently underway under CARB support);

(Objective #3), to compare exposure estimates derived from interpolation of community monitoring stations with those derived from microenvironmental and personal sampling information collected in the course of the study -

This objective was achieved and is described in the body of the report, with regard to community and microenvironmental sampling information. Personal sampling information was not obtained in the course of this study due to the lack of a validated personal ozone monitor. As the report details, prediction of residential ozone concentrations may be possible based on community station data in many locations, but prediction of residential PM exposure levels based on community monitoring information is not warranted at this time;

(Objective #4), expand the existing data base on current levels of indoor air contaminants -This objective was achieved, in that a substantial body of data has been collected characterizing the operating conditions of a sub-set of Southern California homes and the indoor and outdoor levels of pollutants during those operating conditions;

(Objective #5), to establish the relationship between indoor and outdoor ozone concentrations, housing characteristics, and air exchange rates in a sub-set of study homes -

This objective was achieved, and is discussed in detail in the body of the report. Observed concentrations, recorded housing characteristics, measured air exchange rates, and models utilizing the collected data base are all presented and discussed in the report;

(Objective #6), to construct a reliable and cost-effective long-term sampler for indoor/outdoor measurement of fine particles and acids;

This objective was achieved. Two-week samplers were constructed and deployed in and around twelve homes to demonstrate the applicability of the two-week sampling approach as a cost-effective method for the determination of fine particle mass and chemistry. The data collected in the pilot project performed is presented in the body of the report.

0.4 Conclusions

This project collected monitoring and survey information in 126 Southern California homes to learn about the potential importance of various housing factors and indoor/outdoor levels of ozone, PM_{10} , $PM_{2.5}$, and formaldehyde. Each home was studied on two discrete occasions, separated by at least 45 days, to permit sampling of the home under different ambient seasonal conditions. Home studies were conducted between February 1994 and November 1994. This investigation revealed the following:

1) Indoor ozone concentrations in homes were typically a fifth of outdoor levels (median I/O ratio of 0.20, inter-quartile range 0.07 to 0.45). No indoor ozone sources of importance were identified;

2) Indoor/outdoor ozone ratios tended to increase during the summer months, concurrent with seasonal increases in ambient ozone;

3) Indoor levels of PM_{10} were usually comparable to, and sometimes higher than, corresponding outdoor levels. In this study, the median indoor/outdoor PM_{10} ratio was 1.05 (with an interquartile range of 0.66 to 1.86), suggesting the presence of significant indoor sources. In a small number of homes, levels approaching 150 to 300 µg/m³ were observed. Across the time period of field operations (summer and fall), no strong relationship with season was observed;

4) In approximately one-fourth of the homes in which PM_{10} sampling was performed, observed levels exceeded the California Ambient Air Quality Standard of $50\mu g/m^3$. The activity and housing factors significantly associated with these elevations included smoking, the presence of mold odors, combustion activities in the home (such as cooking or wall furnace use), air-moving activities (such as dusting or air conditioning), and building construction factors (foundation type, recent remodel, an attached garage);

5) Indoor levels of PM2.5 were usually comparable to, and occasionally higher than, corresponding

outdoor levels. In this study, the median indoor/outdoor $PM_{2.5}$ ratio was 1.10 (inter-quartile range of 0.84 to 1.68), suggesting the presence of significant indoor sources. Across the time period of field operations (summer and fall), no strong relationship with season was observed;

6) Formaldehyde levels were very low in most homes (0 to 39 μ g/m³ [0.03 ppm]), and the median indoor/outdoor ratio was 3.2;

7) Median air exchange rates (AER) were measured at 0.7 hr⁻¹ across a wide range of Southern California homes, and did exhibit some seasonality. AER was more variable and higher during the summer, reflecting resident preference for natural ventilation (opening windows) over the use of home air conditioning;

8) Prediction of residential ozone concentrations (both immediately outdoor and inside the home) based on community station data may be possible in many sampling locations;

9) Prediction of residential PM exposure levels (both outside and inside the home) based on community monitoring information is not feasible at the present time;

10) Efforts to develop models to accurately predict indoor levels of ozone, PM_{10} , and $PM_{2.5}$ based on ambient concentrations, housing factors, and interviews with residents about activities in the home and operation of the home during sampling, met with moderate success;

11) Improvements in regional human exposure models (such as REHEX), by providing improved estimates of ozone and PM, can be made by using the data collected in this study, but is limited by the model's need for 1hr time-resolved ozone data and the data set's applicability of the PM modeling discussion to non-smoking residences;

12) Sampling in residences for airborne levels of acids and fine particle chemistry, using the TWS, is feasible and should be considered for future application.
0.5 Recommendations

Based on this study and the conclusions drawn from it, the following recommendations are made by the study investigators:

1) Personal O_3 and PM measurements are needed to provide information for use in modeling efforts. Information of this type is critical for the improvement and validation of regional human exposure modeling, would provide important information to compare personal exposure levels to indoor and outdoor concentrations, and could provide insights into the microenvironmental exposure of children and adults living in homes with high PM or ozone levels, or helping to explain significant changes in health indices in children participating in the CARB-supported Children's Health Study;

2) Additional study is needed to account for the observation of lower PM loadings reported immediately outside homes compared to those measurements reported from community monitoring sites. Assessment of the relative importance of potential explanatory factors, such as vegetation canopies or localized wall effects around the home, should be resolvable with a focused sampling study designed to unravel this apparent difference.

3) The apparent disparity in community ozone monitoring information between and among specific community stations (such as Lake Gregory and Lake Arrowhead, Riverside and Rubidoux, and Lancaster) should be investigated. If confirmed, corrective action, up to and including possible relocation of existing stations, should be considered.

4) The archived filters collected in the course of particulate monitoring for this study should be chemically analyzed. Gravimetric comparisons of indoor and outdoor levels may accurately reflect relationships, but chemical speciation for sulfur and other constituents could help to more definitively establish the contribution of indoor sources to observed PM levels; 5) Information about the strength, nature, and source of the relationship between outdoor and indoor PM_{10} and $PM_{2.5}$ levels, in varying modes of home operation (such as the home sealed during the day, or with windows left open) is needed to improve human PM exposure assessment. A sampling study indoor and outside of a population of homes operated in a limited and directed representative number of modes, would provide the needed information.

6) The Two-Week Sampler (TWS) is a viable and cost-effective platform for the collection of information about the distribution of airborne acids and fine particle chemistry in and around homes. Based on the pilot demonstration sampling performed in this project, a larger deployment of the sampler should be planned and performed to evaluate the potential for prediction of longer-term residential acid exposures based on community monitoring information. The suggestion of elevated indoor levels of formic and acetic acids, based on the limited pilot sampling data collected in this study, could also be addressed in the course of such an investigation.

1. INTRODUCTION

The project reported here was designed to advance the fields of exposure assessment and air pollution health effects research through direct collection of field data and subsequent modeling of the observed results. The following sections describe the goals of the project and the basis for them.

1.1 Study Aims

The goal of this project was to gather exposure assessment information for use in improved modeling of human air pollution exposures. This was accomplished by collecting air sampling information in and around 126 homes of a sub-group of children participating in a cross-sectional air pollution health effects study (California Air Resources Board [CARB] Contract #A033-186). Measurements made in the course of the home sampling study included the determination of indoor/outdoor ozone, indoor/outdoor respirable particulate matter (both PM_{10} and $PM_{2.5}$), indoor formaldehyde, house air exchange rates, and some limited pilot information regarding indoor/outdoor levels of airborne acids.

The specific objectives of the sampling effort were:

 (1) to assess the applicability of the Regional Human Exposure (REHEX) model, and modify it, as appropriate, to address large-scale epidemiologic investigations;
(2) to validate the REHEX model using collected exposure data;
(3) to compare exposure estimates derived from interpolation of community monitoring stations with those derived from microenvironmental and personal sampling information collected in the course of the study;
(4) to expand the existing data base on current levels of indoor air contaminants;
(5) to establish the relationship between indoor/outdoor ozone ratios, housing characteristics, and air exchange rates in a sub-set of study homes;
(6) to construct a reliable and cost-effective long-term sampler for indoor/outdoor measurement of fine particles and acids. The absence of a validated acceptable personal ozone sampler for use in the study precluded complete achievement of all six project objectives. However, project objectives not relying on personal exposure information (objectives #4-6) were achieved in the performance of the project, and significant progress was made towards meeting those objectives requiring a validated personal ozone sampler (objectives #1-3).

1.2 Rationale

In the past, potential insights gained from air pollution epidemiology studies have often been limited by the quality of pollutant exposure information available. Traditional air pollution epidemiology investigations have typically used fixed-site outdoor monitors to assign exposures to study populations (NAS, 1991). This approach has been based on the premise that samplers sited for regulatory-based compliance monitoring will provide adequate exposure characterization of the study population of interest.

When pollutants vary gradually over a broad region and display similar outdoor and microenvironmental concentrations, these are appropriate scientific assumptions. However, when pollutant concentrations in different microenvironments vary due to local sources or the reactive nature of the pollutants themselves, exposures measured by a central outdoor ambient monitor can misclassify true population exposure.

Assessment of the important microenvironments in which human exposures occur begins with identification of the microenvironments of importance. Recent investigations have revealed that Californians spend the vast majority of their time indoors, with most of that time spent at home (Jenkins et al 1992), and that children spend about 86% of their time indoors (Wiley et al 1991, Phillips et al 1991). It is therefore critical that indoor pollutant exposures, especially those in and around the home, be considered in assessing population exposure.

Ozone, nitrogen dioxide (NO_2), respirable particulate matter (PM), and acids are ambient pollutants of regulatory and research interest potentially prone to misclassification. Ozone interacts readily with surfaces and would decay rapidly to very low concentrations in a residence with low air exchange rates (the rate at which a complete replacement of the air in a given microenvironment occurs). Low air exchange rates lead to a long average residence time for each parcel of air entering the home, allowing time for the reactive ozone molecules to interact with materials in the home and decay (the lack of any appreciable indoor residential source of ozone makes it appropriate to consider reactive decay of outdoor ozone only).

However, indoor/outdoor ratios can vary from being very low in residential settings using air conditioning (Stock et al 1985) to being considerable, in commercial buildings with active ventilation and filtration (Weschler et al 1989). A number of residential measurements made in Houston (Stock et al 1985), as well as several made in former Southern California homes now used as museums (Druzik et al 1990), have observed this predicted reduction. On a regional scale, little is known about the relationship between ozone levels observed at regulatory network monitoring sites and exposure concentrations immediately surrounding and entering homes; vegetation canopies and surface effects could influence observed concentrations. In homes having a high air exchange rate, outdoor pollution levels may well be a good predictor of indoor air quality. Indoor air would rapidly exchange with outdoor air, and an outdoor and reactive contaminant, such as ozone, could achieve indoor levels that approach those found outdoors.

For airborne particles, the indoor environmental burden can vary dramatically. Outdoor particulate concentrations are suspected to be poor indicators of both indoor concentrations and personal particulate exposures (Clayton et al 1993). Indoor sources of particulates, and the large amount of time that people spend indoors, are thought to account for this poor association.

Few studies, however, have characterized indoor particulate levels. Studies conducted to date have found that significant fractions (50-90%) of outdoor PM_{10} and $PM_{2.5}$ penetrate indoors (Clayton et al 1993, Koutrakis et al 1992, Thomas et al 1993). Once indoors, both PM_{10} and $PM_{2.5}$ may deposit onto surfaces, or may be depleted through volatilization (as with ammonium nitrate) or through reactions with other compounds present (such as the neutralization of sulfuric acid by ammonia). Production of PM_{10} from such common sources as indoor cigarette smoking, cleaning, wood burning (from fireplace usage), and certain hobbies (such as woodworking and

soldering) can also significantly elevate indoor PM levels (Pellizari et al 1992, Koutrakis et al 1992).

Sources of NO_2 are present in virtually all combustion processes. Indoor sources include cooking and heating units (such as gas and propane stoves, ovens, and space heating systems) appliance pilot lights, and fireplaces. In urban California areas, outdoor NO_2 concentrations tend to dominate average NO_2 exposures measured over days or weeks, and account for a substantive portion of personal exposure (Colome and Wilson, 1989, Hackney et al 1992).

Relatively little is known about indoor and spatial distribution of ambient acids, and few data sets exist, except for limited special-study investigations. In the ambient setting, regulatory agency monitoring stations rarely collect such data routinely in any systematic sustained manner, since few jurisdictions regulate acidic pollutant levels. In and around the home, relatively little is known about the intrusion of ambient acid levels. Outdoor nitric acid levels should be rapidly depleted by surface reactions indoors, but indoor sources from combustion appliances such as gas ranges or unvented heaters may provide additional contributions. Other acids, such as nitrous acid, are elevated indoors. Few studies have reported on residential levels of organic acids, such as formic and acetic.

Exposure of Californians to formaldehyde has been recently evaluated, due to reporting requirements associated with CARB's classification of formaldehyde as a toxic air contaminant. Indoor exposures of formaldehyde have been previously assessed by several studies, and have been related to the house age, which is a likely index for the building materials used, and a reflection of the outgassing of formaldehyde from composite materials containing organic adhesives. Newer structures might be expected to have higher levels of formaldehyde, due to wider use of synthetics, composites, and resins in construction, home furnishings, and finish carpentry.

Development of effective models to estimate and categorize human exposure to these and other pollutants of regulatory and health interest requires improved information regarding the relationships between indoor and outdoor pollutant concentrations and the housing characterization factors that may help to predict them. Recent advances in exposure measurement offer the promise of more accurate estimation of exposure. Improvements in exposure specification offer the possibility of more accurate prediction models for personal exposure, which would provide the regulator and researcher with more precise information about the implied or actual health risks associated with exposure to specific levels of identified pollutants of regulatory concern.

1.3 The Children's Health Study

In 1992, the California Air Resources Board provided support for an ambitious multi-year project designed to assess the potential chronic health effects of air pollution in California children (CARB Contract #A033-186). Approximately four thousand California public school children in twelve Southern California communities were enrolled into the project. Participation involves annual lung function testing and medical history updates, residential history and activity pattern surveys, and a detailed exposure assessment component. Selection of study communities was based on an attempt to satisfy an experimental design seeking to exploit the observed or predicted ambient variation in community ozone, PM10, NO2, and acid concentrations. Communities with historical monitoring data near the high or low ends of the ambient exposure distribution for ozone, particles, oxides of nitrogen, and acids were selected for study. The existing regulatory monitoring stations in each of the twelve study communities were augmented with monitoring instrumentation, as needed, to provide continuous ozone and NO₂ data, hourly PM_{10} data, and aggregate two-week averages of fine particles and acids. In addition, a substantial effort was undertaken to characterize ozone exposure in participating school classrooms, and several personal ozone sampling experiments were performed to validate a personal ozone sampler for study use. The progress and performance of the Children's Health Study has been reported in a separate contract report to the Board (Peters 1995).

1.4 Research Questions To be Addressed

By utilizing the study population and exposure assessment activities established through the Children's Health Study, a unique opportunity was available to cost-effectively expand knowledge of how microenvironmental and personal exposure to specific pollutants (ozone, PM_{10} , $PM_{2.5}$, acid, and formaldehyde) impacts total exposure.

The research questions suggested by the study proposal (Avol 1992) include:

(1) Have residential ozone exposures been over or underestimated

by using outdoor central station data?

(2) What level of protection from ambient ozone exposure is afforded Californians by staying indoors during elevated outdoor ozone episodes?

(3) What can be said about the distribution of PM_{10} exposures in and around California residences?

(4) Is there a variation in seasonal indoor and outdoor concentration of PM_{10} ? (5) Can a long-term fine-particles/acid sampler be developed and deployed in community and residential settings to obtain cost-effective information about exposure to acids?

(6) What can be said about indoor residential concentrations of formaldehyde?

(7) What is the relationship between indoor and outdoor concentrations of formaldehyde?

The information generated from the research project reported here will help provide the basis for assessment, further development, and validation of a human exposure model to be used in large environmental epidemiological studies.

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1-8

2. STUDY DESIGN AND METHODS

2.1 Introduction

Several meetings with technical personnel from the Children's Health Study, the CARB project office, and this project's research team were held to develop a research approach that would permit collection of the types of information needed by modelers, researchers, and regulators. Based on these discussions, and the inherent fiscal limitations and time constraints imposed on the research project, a design approach was developed and performed. The following sections describe the scientific approach and field methodology employed to perform the project.

2.2 Sampling Considerations

The study population on which the residential sampling project was performed were those residences housing students participating in the Children's Health Study (CHS). Since the CHS study population included over three thousand homes in twelve different communities of differing air pollutant mixtures across Southern California, several stratification and selection schemes were considered prior to accepting one for study application.

Assessment of housing factors during two seasons of the year, which might offer sampling opportunities under differing modes of house operation (such as windows left open in the more temperate season, and the home better sealed for heating or air conditioning at other times of the year) was agreed to be important, so the study was designed around a two-visit sampling protocol in each potential sampling home. The anticipated costs associated with performing sampling in and around homes to quantify the stated pollutants of interest (indoor/outdoor ozone, indoor/outdoor PM_{10} and $PM_{2.5}$, air exchange rates, and formaldehyde) limited the potential sampling pool to a maximum of 150 homes, to be studied on each of two occasions. This level of sampling was determined by investigators to be feasible using the sampling protocol described in the original proposal (ozone sampling performed using small passive samplers developed by the Harvard School of Public Health and commercially available through Ogawa USA, PM sampling using personal hygiene sampling pumps, air exchange rates by perfluorocarbon tracer, and formaldehyde using sampling pump/cartridge collection). Visiting 150 homes within the available study period proved to be infeasible due to subsequent changes in the actual protocol

regarding the collection of ozone samples in and around the home. Problems associated with the use of the passive ozone monitor complicated field sampling operations by requiring larger, more labor-intensive instrumentation be used to collect the necessary ozone information (see Section 2.4.1).

2.2.1 Stratification and Community Selection

The operational goal of the residential exposure study was to perform indoor/outdoor sampling in 150 residences of students participating in the twelve-community Children's Health Study. In addition to the considerations summarized above, sampling from more then one study community was also deemed to be important. This decision was based on several reasons. First, sampling from several communities provided increased opportunity for a range of observable ambient pollution levels, since the twelve-community pool represented a range of ambient air quality with regard to historically observed levels of ozone (O_3), particulate matter (PM), oxides of nitrogen (NO_x), and acids. Credible information about indoor intrusion rates for most of these pollutants was lacking (with the possible exception of NO_x , for which a substantial amount of in-home sampling information had previously been collected in other investigations), and information about indoor/outdoor ratios over a range of conditions was considered to be valuable for exposure assessment.

Secondly, home selection from several different communities, in principle, should have helped to counter-balance some potential experimental design biases related to area-specific factors, such as different types of housing construction, age differences in the housing stock (which might affect housing tightness), and area climatic differences relating to home operations (leading to differences in door and window use, which could affect observed air-exchange rates, and indoor/outdoor ratios).

Specific community selection was acknowledged to be dependent on study emphasis. Choosing communities from both high and low ambient pollution locales would enable estimates of indoor/outdoor differences to be made across a wide range of ambient levels. Choosing communities from areas of high and medium level air quality, however, might provide more precise estimates of differences within a more limited range of ambient levels likely to be associated with health effects (which could be of use in the Children's Health Study research effort). This sampling approach would potentially provide more accurate estimates of personal exposure for subjects likely to exhibit health effects, at the cost of less accurate estimates of indoor-outdoor differences in communities with low ambient levels.

The limited scope of sampling in this project (150 homes maximum) argued strongly for a focused approach to community selection. Of the four pollutants (O_3 , PM, NO_x , and acid) identified as the primary focus of the CHS investigation, the first two were judged more likely to be important at ambient pollution levels (from a human health standpoint). Selection of sampling communities was therefore focused on historical ozone and PM information.

Ranking of the twelve potential communities, based on recent historical (1986-1990) ambient air quality information collected at agency monitoring stations, resulted in the following designations:

High O₃, High PM Lake Elsinore Lancaster Mira Loma Riverside San Dimas Upland

Low O₃, High PM Long Beach High O₃, Low PM Alpine Lake Gregory

Low O₃, Low PM Santa Maria Lompoc Atascadero

The sampling strategy for the residential study called for measurements in each of the 150 homes on two occasions, once in each of two distinct climatic time periods. Investigators believed that selecting homes in the more highly polluted areas, and sampling in these homes during periods of both seasonally-anticipated high and low pollution events, would efficiently

maximize the range of sampling events. O_3 and PM have strong seasonal patterns (O_3 highest in the summer, and lower other seasons of the year; PM highest in winter, moderate in spring and fall). Given the seasonal variation in air quality, it was judged to be unnecessary to study homes in low pollution areas, since this type of "low pollution" information could be collected in the high pollution sites during the off-peak pollution season.

In conformance with these considerations, community selections were chosen to represent high ambient O_3 and PM_{10} sites. (From the ranking above, candidate communities are listed under "High O_3 , High PM" and "High O_3 , Low PM" designations and include communities primarily east of the Los Angeles metropolitan area and downwind of its pollution contributions).

Air conditioner type was thought to be an important determinant of indoor-outdoor differences for many pollutants, and especially for reactive contaminants such as ozone. Residential air conditioning systems were grouped into four types: central, wall, evaporative (or "swamp"), and none. Initial survey information describing the homes available for study participation was reviewed. A summary of the tabulated data appears as Table 2-1, based on some 3200 CHS households responding.

The data revealed an overwhelming presence of central air conditioning in homes reporting air conditioning units; few room units were reported. This may reflect newer home construction trends and/or some confusion on the part of study respondents. Regardless of the explanation, it is clear that central air units dominated the housing population under study consideration.

With the possible exception of Lancaster, swamp cooler presence appeared to be minimal. An apparent concentration of swamp cooler-based systems in the Lancaster (high desert) area made that area worthy of consideration for possible sub-set study sampling (the high air exchange rates of swamp cooler systems coupled with the low water solubility of ozone made homes serviced by swamp coolers prime candidates for increased indoor ozone levels). Ten of the twelve study communities reported a number of homes without air conditioning (Lancaster and Upland being the exceptions). Non-air conditioning homes from each community were deemed important for study to address issues of ventilation rates in homes within a community (i.e.,homes effectively sealed for air conditioning use compared to homes with doors and/or windows open for ventilation).

In a similar manner, the possibility of home selection based on appliance type (such as the use of a gas or electric cooking range in the home) was considered. Particle levels in the home might well be affected by the presence of a gas stove, but assignment of exposure by the mere presence of a gas stove could lead to exposure misclassification, due to other confounding factors (such as infrequent use of the stove, frequent use of a range hood, or regular use of a microwave oven). Even if potential exposure could be well-defined, the available sampling distribution seemed to be badly skewed. Respondents to the housing survey reported that, with the exception of Alpine, communities were typically composed of 83% gas and 17% electric homes (Alpine was closer to a 50/50 mix). Additionally, the percentage of residences without air conditioning was less than 20% in the high O₃/high PM communities under consideration. This suggested that it would be difficult to create a balanced design based on air conditioner and appliance usage, since there were likely to be very few residences in the no air conditioner/no gas stove category. Since no explicit hypothesis about appliance use having a strong or consistent effect on indoor-outdoor ozone differences could be clearly proposed or assessed with the available study population, home selection based on appliance use did not seem warranted and was not done.

With respect to PM in the home, the presence of smokers in the home would be expected to change patterns of PM loading and distribution. Having no reason to believe that smokers preferentially congregated in or away from any one of the study communities under consideration, it was assumed that smoking prevalence would be similar across the communities studied. Preliminary survey information, collected from all CHS study participants, suggested that smoking activity in the home varied across CHS communities. Smoking activity varied from 16% of CHS study homes in Upland to 46% of CHS study homes in Lake Elsinore, with most

CHS communities in the 25-35% range (see Table 2-2). Accordingly, plans were made to document the presence of actual "smoking" homes in the residential sampling project through survey techniques during actual home sampling operations, with the expectation that a portion of homes in each community would contain smokers. However, the selection of sampling homes for residential study participation was not based on previously demonstrated evidence of smoking activity.

The above reasoning led to the selection for sampling of the following four communities: San Dimas, Mira Loma/Riverside, Lancaster, and Lake Gregory. San Dimas (within a few miles of the Glendora district air monitoring station) was representative of sites historically reporting some of the highest ozone levels observed in the Los Angeles area. It was selected over Upland based on historical data suggesting levels might be higher in San Dimas and based upon preliminary survey results which suggested that virtually all of prospective participants' homes in Upland had air conditioning (i.e., a lack of non-air conditioned homes in the sampling community).

Homes from the Mira Loma/Riverside area were selected to represent an area high in PM and ozone. The ambient PM burdens, as well as the neutralized nature of that PM, made that area an important site to consider. The geographical proximity of these two areas (city borders virtually touching each other) made grouping of the housing stock, for the purposes of this sampling study, a reasonable approach.

Lancaster was chosen for the unique sampling opportunity it represented with regard to a possible sub-study of air conditioning usage effects on indoor ozone intrusion rates. Housing survey responses reported a number of swamp coolers for home air conditioning use (which might be representative of homes with increased intrusion rates of ozone) in the Lancaster area. Lancaster's pollutant background (elevated levels of O_3 and PM), and its climatic conditions (which might provide a slightly different pattern of housing operation and air exchange than the other communities) also made it an attractive study site. Lake Gregory (including the Lake Arrowhead area) was selected to provide some housing stock from an area high in ambient pollution (ozone) with potentially different home operating conditions. The general absence of homes reporting air conditioning units in this community suggested differences in door and window use, compared to other communities under investigation. More dramatic seasonal weather (snow, sleet, and rain) than that typically seen in most of the other study communities might also suggest differences in housing tightness and operation. Finally, geographical proximity to Los Angeles-based investigators, as compared to Alpine (located some 40 miles east of San Diego), made it a study site of choice.

In summary, the design criteria led to a sampling design involving a maximum of 150 homes, in approximately equal numbers, from the communities of San Dimas, Mira Loma/Riverside, Lancaster, and Lake Gregory. Sampling was to be performed once in each home during each of two seasons. Homes were selected based on preliminary survey information regarding air conditioning. Homes without air conditioning were also sampled from each of the four target communities, and homes reporting the presence of a swamp cooler for air conditioning were of particular study interest.

2.2.2 Home Identification for Recruitment

Residences were randomized for assignment of formaldehyde, air exchange rate, and particulate matter sampling. Each home was monitored for ozone. Those homes accepted into the study for a specific type of measurement (e.g., respirable particulate matter) were sampled twice, according to study design. Since every measurement was not planned to be completed in each home, it was necessary to develop an approach for assigning which homes would receive which measurements.

Under the system shown in Table 2-3, before a home was recruited, it was randomly assigned as an A-E residence. When a residence was assigned as an A home, for example, all possible measurements were scheduled to be made in that home at least once. This approach guaranteed that at least a small number of homes would have multiple measurements, allowing for evaluation of the inter-relationship among the measures taken.

From the 150 homes to be monitored, 25 sampling opportunities were reserved for swampcooled homes. Swamp-cooled and non-swamp-cooled homes were allocated in the same proportions to the five types of home sampling ensembles (A-E), with rounding differences arbitrarily assigned (see Table 2-4).

The sampling assignment for the 125 non-swamp-cooled homes was distributed evenly among the four communities (see Table 2-5). Swamp-cooled homes were assigned without respect to the community from which they were drawn. This had the effect of increasing the proportion of the overall sample of 150 homes from the communities of Riverside and Lancaster (areas which had a higher proportion of homes with a swamp cooler).

Each home type (A-E) specified a particular instrument ensemble. These ensembles were randomly ordered for homes within each community, and every attempt was made to adhere to the sampling ensemble directive. For swamp-cooled homes, a separate randomized list was generated for use in order assignment (see Table 2-6). Using this listing, swamp-cooled homes were outfitted with the appropriate sampling ensemble, regardless of the specific community in which the home was located.

Field technicians proceeded with home recruitment according to the order in each list (working from top to bottom). For example, if the first opening on the list was a B home, the field representative recruited their next home as a B home.

2.2.3 Home Enrollment

Prospective study homes were identified using a computerized listing drawn from the larger population pool reported in the baseline medical/residential history questionnaire, which was completed by some 3200 epidemiological study participants during Spring 1993. From the list of eligible homes, a randomized list of initial contacts was generated. Residents were contacted by telephone and/or mail and invited to participate in the study.

After the pool of study homes was selected, specific measurement assignments were made

to each home (see Section 2.2.2 above) since the project resources did not permit taking measurements of each species in every home.

Homes were studied on a rolling basis, with an initial target of eight homes per week to be monitored throughout field operations. The technicians scheduled home visits at the convenience of the resident.

Initial contact with prospective residential study participants was made through the mail, followed by a telephone conversation and an invitation to participate in the project. Technicians also were encouraged to make personal contact and visit the residence while working within the neighborhood, knocking on the door to ask about the subject's possible participation in the residential study. If a household refused to participate, or did not respond to written inquiries, efforts were undertaken to change have the matter reconsidered and obtain the resident's consent for study participation. Study recruitment goals were to achieve a high participation rate to avoid the potential criticism that the results obtained from this study were due to participant bias (or self selection).

2.2.4 Study Participation Rates

As described in the previous section, participants in the residential study were selected from the defined population of students participating in the CARB-supported Children's Health Study (CHS). Specific results from this report relate directly to this population of homes which, by definition, contain school-aged children. As such, the sample and results from this investigation may not generalize to a larger sample from a wider geographic region and with a broader demographic distribution.

Through a procedure described previously (see Section 2.2.1, Stratification and Community Selection), a subset of the twelve CHS communities were selected for participation in the current investigation. The potential sample of homes to be studied in the residential survey (150 total) was too small to study all twelve CHS communities, so communities were selected on the basis

of air quality considerations, logistics, and the presence of air conditioning units. Potential study residences were randomized, and this listing was used by the field technicians to recruit households for participation.

A formal protocol was established for the field technicians to recruit participants into the residential study. Log sheets were created to record attempts to contact and recruit residents of potential study homes. In order to keep up with the sampling study schedule, it was necessary for the field technicians to continue down the randomized listing, contacting new prospective participants before exhausting the maximum number of contact attempts for some of the previously contacted participants. This approach had the effect of increasing the denominator in our participation rates, which made the calculation meaningless. It was our subjective impression that no systematic bias was introduced by this approach (but this approach did result in some prospective study residences receiving initial phone contact attempts but no follow-up calls to resolve whether or not they would be participants). Because of this series of events, participation rates were not computed.

2.3 Survey Information

In addition to the actual air sampling performed in and around each of the study homes, three types of questionnaire surveys were used to collect descriptive and explanatory variable information about the study residences. The "Baseline" questionnaire was completed by the parents and legal guardians of children participating in the Children's Health Study, as part of initial CHS study enrollment in Spring 1993. The "Technician" questionnaire was completed by field staff personnel, during a walk-through survey conducted in the study home, to document housing characteristics of potential study importance. The "Follow-Up" questionnaire was completed by field staff personnel, with the help of adult residents, immediately following sampling in a given home, to document the actual characteristics of home operation during the sampling period.

2.3.1 Baseline Questionnaire

The Baseline questionnaire sought information in three broad categories - medical history and family health status of the child participating in the Children's Health Study, temporal and spatial activity pattern information of the participating child, and residential history information focused on the current residence of the child. With respect to the residential exposure study, those questions relating to home characteristics were of particular importance.

As described in a previous section, homes were stratified for enrollment into the study after reviewing baseline questionnaire responses to written questions about heating and cooling of the child's home, appliance usage, and smoking activity in the home. Selected sections of the Baseline questionnaire, which are relevant to the residential exposure study, are presented in Appendix A.

2.3.2 Technician Survey

The Technician survey was developed to provide objective verification of current housing characteristics at the time of site sampling. The questionnaire was completed by field staff personnel through direct observation of the home during a walk-through visit, rather than obtaining information by interviewing the resident. Approximately half of the eleven-question survey was derived from previous home sampling studies (such as CARB-supported PTEAM and Woodland projects) and half were newly developed. For convenience and comparability, the source of the specific question used in the survey was identified on the survey. A copy of the Technician survey is contained in Appendix B.

2.3.3 Follow-Up Survey

The purpose of the Follow-Up survey was to document the actual status of specific housing factors that may have affected sampling in or around the home. These factors included documentation of pollution-generating activities such as vacuuming, barbecuing, and dusting, the use of air conditioning or heating, and the opening of windows and doors. Twenty multiple-part questions were completed during a brief interview with the resident upon conclusion of sampling. Three-fourths of the questions used were drawn from previous CARB-supported home sampling

studies (such as PTEAM and Woodland), and the remainder were newly developed. As with the Technician survey, the source of included questions in the Follow-up survey was listed in the questionnaire for ease of referral. A copy of the Follow-Up survey appears in Appendix C.

2.4 Monitoring Variables and Logistics

This study's characterization of intrusion of outdoor pollutants into homes included measurement of six specified monitoring variables: ozone, PM_{10} , $PM_{2.5}$, formaldehyde, air exchange rate, and a feasibility study using a novel PM/acid sampler. A summary table of the sampling design is presented in Table 2-7.

Samplers were operated for a twenty-four hour (24hr) collection period, except for the PM/acid sampler, which was designed to operate for two consecutive weeks (and therefore identified in discussion as the two-week sampler, or TWS). Generic siting criteria for all indoor samplers included sampling in the residential room of central activity (usually the den or family room), locating monitoring instrumentation away from entry doors or windows, and sampling from a height of at least one meter above the floor. Residents were encouraged to continue on with normal room use activities (but many commented on the pump noise associated with equipment operation, and most likely modified their daily routine somewhat to reduce use of the room being sampled). Siting criteria for samplers immediately outside the homes included placement of the samplers on the rear patio or porch (for security reasons, as well as access to house line current), sampling from a height above the floor surface at least one meter, and avoidance of any tree canopies, roof overhangs, or home air vents. The sampling approach and design are summarized in sections below by measurement variable. Additional and more detailed information is presented in the project Quality Assurance Plan, submitted previously to the CARB project office (Avol and Colome, 1993). Data reduction approaches for the air monitoring variables are detailed in Appendix D.

2.4.1 Ozone

The original sampling plan involved the simultaneous measurement of both residential and personal ozone concentrations. The plan was to assess the intrusion of outdoor pollutants into

residences and to compare fixed-site measurements, made in the home or at the community monitoring station, with personal sampling, which would potentially incorporate sampling across several microenvironments (such as various indoor locations, outdoor locations, and in transit or travel vehicles).

The original sampling protocol was developed around the anticipated use of a passive ozone sampling device, developed by Koutrakis and co-workers (Koutrakis et al 1990, 1992) and commercially available through Ogawa USA. During validation sampling performed under laboratory conditions in the early stages of the Children's Health Study, the sampling performance of the passive Ogawa ozone sampler was found to be unacceptably variable due to apparent changes in effective sampling face velocity and possible sampling face starvation effects (Lurmann et al, 1993). To deal with these potential sampling biases, a controlled flow sampler, which permitted timed exposure diffusion (TED) sampling of the Ogawa sampler cartridge, was developed for ozone sample collection in the CHS study. The TED sampler was evaluated and found to be free of the sampling biases associated with the passive use of the Ogawa sampler (Lurmann et al, 1993).

In view of these events, the sampling approach used to collect ozone concentration information in the residential sampling study was revised to include the TED sampler, instead of the passive sampler originally proposed. This difference in sampling approach had at least two implications for the residential exposure study. The first resulted from the significant difference in physical size between the passive Ogawa ozone sampler and the TED sampler (the passive sampler being about the size and weight of a roll of stamps, and the TED sampler being the size and weight of a typical toolbox). This size and weight difference made transport, storage, deployment, and general handling a more significant issue than originally planned. Consequently, home installations for sampling, transport of equipment from sample home to sample home, and scheduling of study homes for testing became more limited by physical logistics than would have otherwise been the case.

Secondly, the toolbox-sized TED sampler weighed several kilograms and operated on house

current (115 volts alternating current [VAC]) for this study (battery operation was a feature of the instrument, but the rechargeable battery used also weighed several kilograms). Size and weight considerations, therefore, negated any personal ozone sampling plans.

The potential for obtaining useful microenvironmental in and around homes, and relating that information to data collected at the community monitoring stations, was judged to be sufficiently high to make it worthwhile to continue the sampling project without the personal sampling component. Therefore, even though personal sampling objectives could not be met, CARB staff and project investigators determined that the study should go forward to address the microenvironmental exposure objectives of the project.

2.4.1.1 TED Sampling

For the reasons described above, TED samplers were deployed for field determination of residential ozone concentrations. Two TED samplers were purchased with project funds, and twenty-eight TED samplers were loaned to the field operations staff from the Children's Health Study exposure assessment group. These were deployed into and around homes according to a prearranged schedule, in conformance with the project design discussed in Section 2.2.2, and by negotiation with the resident.

During residential sampling field operations, TED samplers were operated on house line current (115 VAC). Sampling was initiated and completed manually, to simplify home installations. Manual operation of the samplers was actually more efficient for the purposes of the project, since manual operation made it unnecessary to take the time to synchronize and electronically program timers for coordinated inside and outside samplers at a given residence, and provided needed flexibility in the field during home installment of instrumentation.

The TED samplers provided a controlled air velocity sampling regime for the Ogawa passive ozone sampler. The Ogawa sampler is a whistle-sized filter holder made of machined Teflon. The sampling substrate is a glass fiber filter coated with a nitrite solution, which oxidizes in the presence of ozone to nitrate. The converted nitrate is analytically determined by laboratory ion

chromatography. The performance of this approach has been previously described (Koutrakis et al 1990, 1992).

Ogawa filter samples were purchased from Ogawa and delivered to the sub-contractor laboratory (at Los Amigos Research and Education Institute - LAREI). At LAREI, in an ozonefree environmental chamber, the nitrite-coated filters were loaded into teflon filter holders for subsequent sampling. The loaded filter holders were sealed in a plastic bag, placed in a press-fit airtight vial, and kept under dark and refrigerated conditions until transfer to the field. Transport to and from the field was performed by study field personnel and documented by chain of custody records, with holders in their individually identified and sealed airtight storage vials. TED samplers were loaded at the study home site with the Ogawa teflon filter holder just prior to sampling initiation. Following the 24hr sampling period, filter holders were removed from the TED samplers, sealed into their plastic bags, and placed into their press-fit airtight vials. Exposed samples were returned to the laboratory as quickly as possible, but were typically kept sealed and refrigerated for several days during transfer from the field to the LAREI facility. Samples were returned to the laboratory and refrigerated until ion chromatographic analyses were performed.

2.4.1.2 Ultra-Violet Photometry

Ultra-violet photometers (Dasibi Corporation Model 1003-AH or equivalent) were deployed in the course of field operations to assess the precision of the TED sampling approach and to provide some insight into the hourly variation of ozone concentrations in and around a subset of sampling homes. To collect continuous indoor and outdoor ozone data simultaneously, two commercial photometers were placed in each sampling home and operated over the same 24 hour sampling period as TED samplers. Both instruments were always located indoors, for temperature control and security reasons. Teflon sampling lines were used to sample from the inside of the home, or through an opening (such as a window screen, doorjamb, or electrical box) to the outside. Instrument siting criteria included placing the sample inlet away from local sources, locating the inlet clear of vegetation, and maintaining inlet distance at least one meter from walls or solid surfaces. Instruments were interfaced to a personal computer system which averaged readings collected over each successive three minute period, and recorded the averaged value to disk. The data file was retrieved upon completion of sampling, and denoted as raw (uncorrected) data. Raw instrumental output data was corrected at a later time, based on pre and post-field use multi-point calibration curves generated with the photometer used in the field and compared to a transfer standard photometer calibrated at the SCAQMD laboratory.

Noise suppression housings were used with the commercial photometers to reduce the objectionable impact of the instruments on the occupants. Computer printer sound-reduction housings were adapted to fit over each monitor. Nevertheless, the resulting package was somewhat cumbersome and still contributed some background noise in the home.

The field operations plan called for the operation of continuous sampling instruments for 24hr periods in ten selected homes during the study. To minimize subject refusal to participate in the overall two-season home sampling, continuous monitoring was only performed during the second sampling visit, and volunteers willing to undergo the experience were sought out among study home residents. Therefore, these homes represent a set of residential case studies selected as a convenience sample.

Deployment of the photometers into study homes required consideration of several other issues, as well. One of the stated goals of continuous sampling was to observe indoor concentration variation in response to diurnal variation in outdoor ozone concentration. Indoor levels of ozone could also be modified by specific home operating characteristics, such as the use of air conditioners, cooling fans, and the opening of windows and doors. Seasonal variation in outdoor temperature and ambient ozone concentration were also considered. Based on these issues, and to increase the potential for observing variation in ozone concentration, deployment of continuous ozone monitors to study homes was concentrated during the summer sampling period.

2.4.2 Particulate Matter (PM₁₀ and PM_{2.5})

Size-selective particle sampling was performed in participating homes using single-stage impactors developed by Marple (Marple, 1989). Two types of sampling heads (MSP Corporation Model 200 PEM) were used in the project - one to collect particles of ten microns (PM_{10}) mass median aerodynamic diameter (MMAD) and smaller, and another to collect particles of 2.5 microns MMAD and smaller ($PM_{2.5}$). With the exception of differences in sampling inlet diameter (for size cut differentiation) and sampler color (to minimize confusion in field use), the PEMs were virtually identical in construction, appearance, and application.

Use of the PEMs in the field was in conformance with manufacturer's instructions. PEMs were routinely inspected and cleaned, as necessary, between home sampling deployments in the field. After cleaning, internal impaction surfaces were coated with pharmacy-grade mineral oil to reduce particle bounce and re-entrainment.

Samples were collected on thirty-seven millimeter (37mm) filters. Initial field sampling operations used glass fiber filters (Gelman Type AE), with a cellulose support pad, for the gravimetric sample collection required. Though the use of glass fiber filters in the PEM samplers were in conformance with the manufacturer's recommendations for impactor substrate use, their use was contrary to the resiential study's standard operating procedures, which specified the use of teflon filters. Moreover, the glass fiber substrate proved to be unsuitable, due to shearing of the filter face caused by the sealing edges of the PEM heads, in spite of careful loading and handling procedures (including the use of a filter-loading jig to minimize sampling head torquing during loading). A significant number of the filters collected in sampling homes during spring field operations showed some measurable loss of filter material. Accordingly, filter media was changed to 37mm teflon filters with poly-olefinic ring (Gelman #R2J037 Teflo), and the filter shearing problem was substantially minimized.

Filters were analyzed gravimetrically on a Cahn 4700 Electrobalance in the LAREI laboratory weighing room and archived for possible subsequent future analyses. Filters were kept in the weighing room for at least 24hr prior to weighing. Weighing room climatic conditions were

monitored and maintained at nominal settings of 25°C and 50% relative humidity. Clean filters were weighed in the laboratory, individually identified and sealed into small petri dishes, and transported to the project field office for study use. Loading and unloading of the PEMs was performed by trained field personnel according to specified procedures utilizing protective gloves, forceps, and clean working surfaces. Filter samples were transported between project study offices and study sites, loaded in the PEM sampling heads or sealed in petri dishes, in an upright orientation.

Particle samplers were deployed in the study homes by field technicians and used to collect 24hr samples, utilizing commercially available personal sampling pumps (BIOS AirPro 6000D Personal Air Sampler) operating on house line voltage at nominal flow rates of four liters per minute. Sampling was manually initiated and terminated by field technicians during home installation visits. PM sampling was performed, as close as possible, over the same 24hr sampling period as other sampling activities in the home (ozone or formaldehyde, for example).

In order to provide comparative information about size-segregated particulate matter in a costeffective manner, a sampling strategy involving collocation of PM_{10} and $PM_{2.5}$ samplers in several study homes was developed and followed. Thus, in addition to separate deployment of PM_{10} and $PM_{2.5}$ samplers in a number of study homes, both types of PM sampling heads were also located side-by-side in a small number of homes.

The deployment of particle sampling equipment in the study homes was performed in conformance with previously established siting criteria. Those siting criteria previously described for ozone samplers (including placement of samplers one meter off the floor, away from wall surfaces, doors and windows, vents, and the like) were similarly proscribed and adhered to for particle sampling. PEMs were placed in upside-down orientation for actual sampling, to avoid issues of gravitational deposition or possible sampling contamination from inquisitive residents. To reduce the noise associated with pump operation for sample collection, pumps were placed into sound isolation boxes in and around study homes, on a fairly routine but as-needed basis (outdoor samplers did not always require sound isolation boxes).

2.4.3 Formaldehyde

Formaldehyde (and other carbonyl compounds such as acetaldehyde) in air were collected using cartridges impregnated with 2,4-dinitrophenylhydrazine (DNPH) and phosphoric acid, following the method of Fung and co-workers (Fung and Grosjean 1981, Fung and Grosjean 1981, Fung and Wright 1986). Flow-controlled sampling pumps, operating on house line current and sampling at about one liter per minute, were used to collect the 24hr formaldehyde samples.

Preparation and analysis of the DNPH cartridges were provided by Fung and coworkers, in their commercial laboratory. Cartridges were prepared *en masse* prior to field exposure and shipped to the field office, where they were stored under dark and cold conditions, as specified by the laboratory. Cartridges were transported to the field in refrigerated containers and deployed for sampling. Following exposure, the samples were transported back from the field in refrigerated containers, and shipped to the AtmAA laboratory for analysis. Analyses of the DNPH cartridges was performed using high performance liquid chromatography (HPLC).

In conformance with the experimental design, samples were primarily collected inside study homes to extend existing information about indoor formaldehyde levels. In a small number of sampling situations, concurrent with indoor formaldehyde sampling, outdoor samples were also collected to provide some comparative data on outdoor levels.

2.4.4 Air Exchange Rates

Sampling to determine air exchange rates in the study homes was accomplished using a perfluorocarbon tracer (PFT) approach based on the method of Dietz and coworkers (Dietz et al 1986). The tracer gas used was perfluoromethylcyclohexane (PMCH), a fluorinated organic compound with background ambient concentrations in parts per quadrillion (10⁻¹⁵). One to two PFT sources (depending on general house volume and expected flow) were placed in a study home at least twenty-four hours in advance of sampling, to permit the PFT level in the home to achieve some equilibrium level. Then, a collection device (capillary adsorption tubes, or CATs) was placed in the main activity room of the home. Collection of the PFT onto the CAT was accomplished by diffusion onto the activated charcoal tube, and was assumed to be a function

of house volume. (Diffusion rates are also known to be sensitive to temperature, but within the range of home operating conditions in a 24hr sampling period, this mean value was assumed to be 25°C, and any correction was considered minor and ignored). Following exposure in the home, analysis of the CATs was performed by gas chromatography (using an electron capture detector) in a service laboratory (at the Harvard School of Public Health).

Preparation and analysis of the PFT sources and the CAT collection tubes was performed at the Harvard School of Public Health. PFT sources and CATs were carefully separated at all times, to avoid contamination of the CATs. PFT sources were transported to and from the field in sealed tins. CATs were similarly handled in a careful sequestered manner.

2.4.4.1 House Volume Measurements

To provide needed information for the determination of home air exchange rates, two types of home volume measurements (one including and one excluding home cabinetry and furniture) were made in the course of the field study. These measurements were made simultaneously during the walk-through survey of the resident's home, in conjunction with the completion of the Technician Survey. Correction factors for most home furniture were based on an inventory of volume measurements developed in furniture showrooms for a range of furniture and furniture sizes; measurements of home cabinetry were made during home visits to quantify possible nonreadily exchangeable pockets of air within the exterior walls of the home.

Determination of the home volume included a sketch of the house floor plan, which became a permanent record of each study house data file. Measurement of room height, width, and length was accomplished using both a conventional metal tape measure and/or an electronic distance measuring instrument [EDMI] (Seiko Instruments Incorporated Home Contractor) to make straight-line measurements. Calculation of house volume was the determined by field personnel and entered, with supporting data, into the study home data file.

2.4.5 Fine Particulate Matter and Vapor-Phase Acids

The need for a generally accepted and cost-effective method for indoor/outdoor sampling of particle-borne and vapor phase acids for both monitoring and health-based studies led to the fabrication and pilot evaluation of a fine particle/acid sampling system. The Two-Week Sampler (TWS) was designed to provide fourteen-day integrated measurements of ambient vapor phase nitric and hydrochloric acids, fine particle (PM_{2.5}) mass and chemistry for inorganic ions of interest (sulfate, nitrate, and ammonium), and organic acids (formic and acetic). The sampler also had the capability (not exploited in the residential sampling study but used in the Children's Health Study), with minor modification, of being used to collect filters for determination of organic and non-volatile carbonaceous species.

For the residential sampling study, the TWS design had three independent sampling legs, all operating at a flow-controlled sampling rate of 0.4 liters per minute. The first leg (denoted as the main sampling leg or Leg A) was devoted to the collection of nitric and hydrochloric acid, fine particle ($PM_{2.5}$) mass, and fine inorganic speciation of the $PM_{2.5}$ mass for sulfate, nitrate, and ammonium concentrations. The collection device on this sampling leg contained an impactor for controlling particle size, a filter pack for the capture of fine particulate matter, and a honeycomb glass denuder to capture vapor phase acids before they could reach the particle filter sampling face.

The second sampling leg, denoted as the organic acids leg or leg B, was employed to collect organic acids, using a chemically impregnated filter pack. Laboratory analysis of the collected filter extract provided information about formic acid and upper limit values for acetic acid; only upper limit values were obtainable, due to known interferences from other ambient organics, such as peroxyacetyl nitrate [PAN], in the measurement.

The third, or auxiliary sampling leg (known as leg C), was devoted in the residential sampling study to providing a replicate sampling path for either leg A or B. (In the twelve-community regional monitoring station network, operated as part of the Children's Health Study, Leg C was used to collect filter samples which were archived for possible future analyses of ambient

elemental and organic carbon levels).

2.4.6 Regional Monitoring Stations

Documentation of daily ambient pollutant concentrations in the communities of study interest was provided by a stationary site monitoring network. The residential study communities (Lake Gregory, Lancaster, Riverside/Mira Loma, and San Dimas) were part of a larger community monitoring network, operated as part of the Children's Health Study, and data from the CHS monitoring network was available to project investigators. Continuous outdoor monitoring data for ozone was obtained in each study community using commercial ultra-violet photometers interfaced to a computerized data logging system. Information about respirable particulate matter (PM_{10}) was collected in each study community using a commercial real-time particle monitor, the Tapered Element Oscillating Microbalance (TEOM). Operation of this instrumentation was performed by network support personnel. The details and operating procedures of the twelve-community operating network are outside the scope of the current study, but may be found in the draft final report for Phase II of the Children's Health Study (Peters 1995).

2.5 Statistical Analyses

The analytical approach used in the analysis of this data set followed conventional and accepted methods of data validation and statistical analysis. Unvalidated data was entered into computerized files for subsequent data manipulation. The data reduction and quality control procedures involving the air monitoring information collected in the performance of this investigation are described in Appendices D and E. Limits of detection (LODs) were determined in a manner described in Appendix E; summary values appear in Table 3-1.

Descriptive summaries were created for specific portions of the data set (such as air monitoring information or questionnaire responses) and reviewed by investigators. Summary statistics were generated to describe the data. Range bounds for classes of analyses (such as ozone data, formaldehyde information, and so on) were established and applied to identify unexpected outliers. The general statistical approach is described in the Statistical Analysis Plan, submitted early in the project (see Appendix F).

The modeling approaches employed to assess potential relationships between and among collected air monitoring information and housing factors are described in the course of the appropriate modeling sections (see Chapter 6).

2.6 References

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Table 2-1, Chil	dren's Health	Study Spr'	93 Baseline	Survey: A	ir Conditioning.
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Community	Air Conditioning		Air Co	onditioning	д Туре	Gas Stove	
	no	yes	central	room	swamp	yes	no
Alpine	75/26%	210/74%	207	3	0	134/46%	155/53%
Lake Elsinore	30/11%	247/89%	234	7	7	216/78%	60/22%
Lake Gregory	278/92%	25/8%	21	0	0	260/85%	44/14%
Lancaster	12/5%	236/95%	212	8	19	222/88%	30/12%
Lompoc	273/97%	6/2%	6	0	0	240/82%	52/18%
Long Beach	154/66%	78/33%	77	0	1	193/81%	42/18%
Mira Loma	48/16%	242/83%	223	10	6	270/92%	22/7%
Riverside	53/17%	258/83%	240	7	3	270/85%	44/14%
San Dimas	39/13%	249/86%	233	7	2	254/88%	35/12%
Atascadero	74/34%	140/65%	139	1	1	172/78%	49/22%
Santa Maria	237/91%	20/8%	14	1	0	214/81%	50/19%
Upland	8/4%	198/96%	196	3	0	150/72%	59/28%
subtotals	1281	1909	1802	47	39		
total responding homes: 3190		3190	air conditioned homes:		1888		
Town	Rank	Community	Smokers	Smokers	Smokers		
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Code	03/NO2/PM/ACID		live-in %	visit %	total%		
1	+	Alpine	22	8	30		
2	+ • + +	Lake Elsinore	32	14	46		
3	+ + - +	Lake Gregory	21	8	29		
4	+-++	Lancaster	25	10	35		
5		Lompoc	21	7	28		
6	•+++	Long Beach	16	5	21		
7	+ + +-	Mira Loma	30	10	40		
8	+++-	Riverside	19	10	29		
9	+ + + +	San Dimas	23	7	30		
10		Atascadero	15	3	18		
11		Santa Maria	20	7	27		
12	+ + + +	Upland	14	2	16		

NOTES:

1) "Rank" refers to high or low assignment of pollution level, based on historical data.

2) "Live-in%" refers to current residents smoking on a daily basis.

3) "Visit %" refers to those smokers in the home on a daily basis.

4) Total % refers to sum of "live-in %" and "visit %".

Ensemble Type	Number of Homes	Number of PM 2.5 Samples	Number of PM 10 Samples	Number of HCHO Samples	Number of AER Samples	Number of TEDS Samples
AB	25 25	100 (I/O;2 seasons) 100 (I/O:2 seasons)	100 (I/O;2 seasons)	50 (I/O; one season) 25 (I: one season)	50 (I; both seasons) 50 (I: both seasons)	100 (I/O;2 seasons) 100 (I/O:2 seasons)
C D E	25 50 25	100 (I/O;2 seasons)	200 (I/O;2 seasons)	50 (l; one season) 25 (l; one season)	100 (I;both seasons	100 (I/O;2 seasons) 100 (I/O;2 seasons) 200 (I/O;2 seasons) 100 (I/O:2 seasons)
TOTALS	150	300	300	150	200	600

:

Table 2-3. Home classification for sampler assignment.

PJF2-3.XLS

Ensemble Type	Swamp Cooler Homes	Non-Swamp Cooled Homes	Study Home Total
A	4	21	25
В	4	21	25
С	4	21	25
D	8	42	50
E	5	20	25
Subtotals	25	125	150

Table 2-4. Assignment of Home Types.

Sampling Ensemble	Riverside Mira Loma	San Dimas	Lancaster	Lake Gregory
A	6	5	5	5
В	5	6	5	5
С	5	5	6	5
D	11	10	10	11
E	5	5	5	5
Subtotals	32	31	31	31

N

Table 2-5. Assignment of non-swamp cooled homes by community.

Sample Ensemble Order	Random Number
D	0.013953617
E	0.061365215
D	0.115670951
С	0.14300283
А	0.163586491
В	0.181252728
D	0.181769855
А	0.18944625
E	0.209890399
D	0.215737294
С	0.249798154
А	0.294366981
D	0.348128545
E	0.362182931
D	0.373068358
С	0.479000963
С	0.479781252
В	0.488099029
E	0.544939419
В	0.642121655
A	0.762952068
В	0.831887784
E	0.879103457
D	0.88637988
D	0.96729484

Table 2-6. Assignment order for 25 swamp-cooled homes.

Variable	Method	Analysis
Housing Characteristics	Three survey questionnaires: (1) Baseline - completed by resident; (2) Technician - walk-through by field staff; (3) Follow-up - completed by staff/resident interview	review and statistical assessment
Ozone	TED samplers loaded with Ogawa filter holders ultra violet photometry for continuous update data	ion chromatography direct reading to computer disk
Particulates	single-stage impactors collecting PM10 and PM2.5 samples on 37mm filters using industrial hygiene sampling pumps	Gravimetric
Formaldehyde	Dinitrophenylhydrazine (DNPH) cartridges exposed using controlled-flow pumps	high performance liquid chromatography
Air Exchange Rates	Perfluorocarbon tracer home release with capillary adsorption tube collection	gas chromatography
Acid Speciation (pilot demonstration)	Two-Week Sampler (modified for in-home use) with several filter cartridges	ion chromatography

Table 2-7. Summary of Sampling Parameters for Residential Study.

3. QUALITY CONTROL

A substantial effort was devoted to establish the quality and credibility of the collected data set. A Project Quality Assurance Plan was prepared and submitted to the CARB project office in the first several months of the project (Avol and Colome, 1993). The document outlined specific operating procedures related to the performance of the project. Several revisions of the document were iteratively requested and prepared, based on CARB staff review and evolution of the project. The last revision of the Project Quality Assurance Plan was submitted, in November 1993, to the ARB project office.

Quality control involves an objective assessment of the collected data set from the project. A summary of the quality control results appears in this section, with a more complete presentation provided in Appendix E.

The determined limits of detection (LOD) for the sampling variables of study interest are presented in Table 3-1. These calculated LODs were based on sample and field blanks collected during the performance of the project. The variable number of assigned blanks was in proportion to the variable number of specific measurement types contracted for and performed. In general, ten percent of the collected samples were assigned as quality control blanks, and an additional five percent were reserved for duplicate sampling.

The calculated LODs associated with the data set collected in this project generally met the LOD goals for the study, and were small enough to permit identification of important differences among sample observations. A summary of the LOD goals presented in the Project Quality Assurance Plan, the LODs actually observed based on the collected data set, and some reported LODs from comparable studies are presented in Table 3-2.

The reported ozone detection level of 5 ppb using the TED samplers was consistent with the 1 to 10 ppb detection levels typically assigned to data collected in ambient monitoring studies using commercial ozone monitoring instrumentation. LOD determinations from this project were in good agreement with those studies utilizing elements of this same sampling approach (that is,

use of the TED sampler, or use of the Ogawa filter sampling technique). Potential improvements in O_3 LOD might be achievable (in future studies utilizing the Ogawa filter approach to document O_3 exposure) if uniform and consistently low background filters could be prepared and delivered for exposure from Ogawa (see Appendix E for a discussion of occasional and seemingly unpredictable variability in background levels of prepared filters).

The particulate matter LOD of 2 μ g/m³ reported in this study was lower than PM LODs reported in other home sampling studies using similar methodology (Thomas et al 1993). Great care was taken in the field and laboratory in the handling and transfer of gravimetric samples. Nevertheless, potential improvements could be made in weighing procedure sensitivity through the use of more automated weighing techniques (that is, newer and more precise instrumentation), an improved and expanded set of calibration weights for the gravimetric measurements, and in improved temperature/humidity control in the weighing/filter handling room. It is also possible that the precision and accuracy associated with PM measurements made in this study could have been overestimated, since a nominal flow rate of 4 liters per minute (based on the flow-controlled output and feedback control setting of the sampling pumps) was used in all volume determinations, rather than using individual pre-to-post flow rate calculations for each sample collected.

The sensitivity of the DNPH cartridge sampling approach for formaldehyde was reflected in the reported LOD of 0.2 μ g/m³ (0.163 ppb). This exceeds the goal of the quality assurance plan (which was 1.2 μ g/m³) and is at least a ten-fold improvement in previously reported LODs for similar studies (see Table 3-2). The extremely low LOD reported in this study is a reflection of the collection method used (DNPH cartridge sampled with a flow-metered pump, followed by analysis using HPLC), compared to less precise, and less expensive, methodologies (such as diffusion or impinger-based samplers, followed by coulometric or spectrometry-based analyses) employed in previous comparable studies. The DNPH approach was utilized in this study at the request of the CARB project office, but for the purposes of screening studies to identify homes with significant levels of formaldehyde, less precise and less expensive sampling techniques may be appropriate.

Based on the data collected in this study, the observed air exchange rate LOD was 1.1 hr^{-1} , for an average size home of 350 m^3 volume (as described in Appendix E, the calculated laboratory detection limit for observable perfluorocarbon tracer was 3.52 picoliters). Larger volume homes and higher air exchange rates will dilute the PFT captured by the CATs. Therefore, this result may be interpreted to mean that, as employed in this field sampling, the method did not reliably estimate AERs in excess of 1.1 hr^{-1} . The reported LOD for this study is somewhat higher than those observed in other similar studies (such as Pellizari et al 1990, who reported an LOD of 3 picoliters).

Several factors affected the accuracy of the AER measurement in this study, and could be improved in future work. The AER approach requires that an assumption be made about homogeneous mixing throughout the home, for the purposes of sample collection. In this study, sources were typically deployed into homes 24hrs in advance of sampling due to field logistic requirements; this may not have been adequate equilibration time for optimal sampling in the homes. When possible, PFT sources should be deployed at least 48 hours to one week prior to beginning the CATs sampling. The collection time employed in this study (24hrs, due to field sampling logistics) was short relative to the optimal sampling duration using this PFT method. This tradeoff was made in order to have the air exchange measurements made in this study cover the same time frame as the air pollution measurements, which were the primary focus of the project. Other factors affecting measurement accuracy included variability in laboratory blank values of PFT on the CATs; laboratory values of CATs (prepared and analyzed by Harvard researchers) were more variable than had been observed in previous studies. The use of additional PFT sources in sampling homes (above the two to four sources used in this study), or increased emission rates obtainable by heating of the PFT sources would offer other potential opportunities for measurement improvement.

3.1 References

E Avol and S Colome, "Residential Microenvironmental and Personal Sampling Project for Exposure Classification: Quality Assurance Plan", California Air Resources Board Contract #92-317, Submitted November 30, 1993.

E D Pellizari, J Spengler, H Ozkaynak, "Nine Home Particle TEAM Study", RTI Report #RTI/166/00-01F, Work Assignment #II-66 prepared for the USEPA under Contract #68-02-4544, (March 30, 1990).

K W Thomas et al, "Particle Total Exposure Assessment Methodology (PTEAM) 1990 Study: Method Performance and Data Quality for Personal, Indoor, and Outdoor Monitoring,"J Exp Anal & Environ Epi, 3,2:203-226 (1993).

Table 3-1. Residential Study Limits of Detection (LODs), based on 3*RMSE.

	LOD	N
TED(1)	5ppb	63
PM(2)	2ug/m3	43
нсно	0.2ug/m3	25
AER(3)	1.1 hr-1	21

- (1) Calculated from lab-blank corrected field blanks
- (2) Based on pooled blanks for PM2.5 and PM10, with 3 outliers removed.
- (3) LOD for AER is a function of residential volume.
 and represents the maximum determinable AER.
 The listed LOD was calculated for an average "uncorrected" volume of 350 m3. Therefore, for an average sized home, the method does not reliably estimate an AER in excess of 1.1 per hour.
 Smaller homes may report AER values in excess of the LOD for a home with an average volume.

Variable	LOD	Averaging Time	Method	Study Reference
O3	8ppb	24hrs	Ogawa in TED in homes	this study's QA plan
	5 ppb	24hrs	Ogawa in TED in homes	this study (Avol et al 1996)
	8-11	28hrs	Ogawa inTED in schools	Lurmann et al 1994
	15-18	12hrs	Ogawa personal	Liu et al 1995
РМ	1 ug/m3	24hrs	PEM in homes	this study's QA Plan
	2 ug/m3	24hrs	PEM in homes	this study (Avol et al 1996)
	8 ug/m3	12hrs	PEM in homes	Thomas et al 1993
HCHO~	1.2 ug/m3	24hrs	DNPH cartridge in homes	this study's QA Plan
	0.2 ug/m3	24hrs	DNPH cartridge in homes	this study (Avol et al 1996)
	12.3 ug/m3	7 days	diffusion sampler in homes	Sexton et al 1986
ΔER	2 hr-1	24 hrs	PET release w/CATs	this study's QA Plan
	1 1 hr-1	24 hrs	PFT release w/CATs	this study (Avol et al 1996)
	1.7 hr-1*	24hrs	PFT release w/CATs	Pellizari et al 1990
	4.3 10-1	241113		

NOTES: ~ at 25 degrees Celsius and one atmosphere pressure,

1 ug/m3 HCHO = 0.815 ppb HCHO;

* calculated AER for Pellizari work based on reported LOD of 3.0 picoliters and use of nominal values from ARB Residential study (see Appendix D of this report).

4. FIELD OPERATIONS

Residential sampling for this project was conducted in a multi-staged manner. In November 1993, sampling was performed in a convenience home sample of two investigator homes by project investigators. This was done to demonstrate feasibility of the sampling approach, to identify potential problems in study execution, and to critically evaluate proposed field procedures and field paperwork. The convenience home sample verified the feasibility of performing the field operations phase of the project, but also identified several areas of potential conflict. The large assemblage of instrumentation, and the resulting noise from the concurrent operation of the sampling entourage, made it clear that noise suppression efforts (such as sound-isolated enclosures and/or a reduction in the number and type of sampling instrumentation installed in a given sampling location) were needed. Additionally, the amount and size of the needed instrumentation had some implications for field operations (including practical concerns about how to efficiently transport all of the necessary equipment to sampling locations). Description of the convenience home sampling pilot, and a report on the observed results, is presented in Appendix G.

Field personnel were recruited, hired, and trained in January and February 1994. Technicians were trained by the project investigators, in conformance with the needs of the project and the procedures set forth in the technician training document, previously submitted to the CARB project office. The field operations team was composed of two field technicians and a field coordinator. The available project instrumentation was divided among the three field team members, home address listings of potential sampling opportunities were provided to each member, and individual and concurrent scheduling of home sampling visits was encouraged.

In late February 1994, routine study field operations began. Initially, scheduling and installation of equipment in study homes proceeded conservatively and cautiously, with two or more field technicians visiting each home to provide logistical support, some additional in-field training, and field experience with opportunity for some technical oversight. During the initial home visits of the study, field technicians were accompanied by project investigators to observe the installation procedure and provide a constructive critique of the home installation process

after it had been completed. After sampling in the first few homes, field personnel began scheduling and sampling individually, to maximize available resources.

CARB project staff requested that the initial data collected from the first several homes be reviewed and submitted early in the project. Accordingly, a compilation of the data set from the initial study homes was prepared and submitted to the CARB project office (see Appendix H, for a report on the first ten homes' sampling results). Twenty-four hour levels of ozone, using the TED sampler, averaged 1-28 ppb. Indoor values averaged less than 25% of outdoor levels. Formaldehyde values were relatively low (2-30 μ g/m³), with indoor values averaging five times higher than outdoor levels. Air exchange rate measurements (AER) in the 0.3-0.9 hr⁻¹ range were measured; the observed average of 0.5 hr⁻¹ was consistent with other measurements of AER performed in the Los Angeles area in the spring (Colome et al 1994).

The PM results from the first ten homes' filter sampling were problematic. Observed concentrations in the first homes sampled ranged from -22 $\mu g/m^3$ to 79 $\mu g/m^3$. Negative weighings (occasions where the post-exposure weight of a study filter, and accumulated sample, is reported to be less than the pre-exposure weight) occurred over 25% of the time. A review of filter handling operations was undertaken with the analytic laboratory, representatives of the PM sampler manufacturer, and colleagues at the Harvard School of Public Health (whose air quality research teams had used these types of PM samplers on previous sampling studies). Shearing of the glass fiber filter face by the sealing edge of the PM sampler appeared to be the primary cause for the observed loss of weight. This problem persisted despite strict adherence to manufacturer's recommendations regarding use of a filter-loading jig to properly position the PM sampling head during the filter loading protocol. The filter-loss problem was ultimately resolved by changing the filter media used in the study, from glass fiber to teflon with a polyolefinic ring (use of the glass fiber filters, though in conformance with manusfacturer's recommendations, was contrary to the project's standard operating procedures, which specified teflon filters). Due to scheduling constraints and a limited opportunity seasonal window for field operations, scheduling of study homes and sampling continued during these deliberations.

Home testing continued through November 1994 on a schedule primarily driven by three considerations: (1) the availability of a sufficient amount and type of instrumentation for specific home installation, (2) the availability of field personnel to install sampling equipment and perform the necessary surveys, and (3) accessibility of homes for study (through negotiations with residents). Sampling in homes continued, without regard to weekday or season, driven by the three stipulations stated and the desire to sample across study communities as much as possible.

Field efficiency in home installations, with regard to multiple home sampling in a given community on a given day or successive days, led to successive multi-day sampling in any given community. This was partially offset by deploying three field technicians for home installations but hampered by a finite amount of equipment that had to be shared among field personnel.

Several unrelated events significantly affected the orderly completion of field operations. Limitations in the amount and type of study instrumentation available for timely home installations (to complete pre-designated sampling ensembles for a given home) were a recurring problem throughout field operations and a major impediment. Attempts to obtain additional equipment, through purchase or loan from other investigators, partially mitigated but did not fully address this problem. A break-in and theft of equipment from one of the research offices at USC resulted in the loss of several project samplers and other personal computers in early June 1994; This event further reduced an already limited amount of available study instrumentation. A series of injuries, including a foot injury (unrelated to the project) and a back injury (claimed to be related to the project), to one of the field staff during the course of field operations reduced the effective field operations team to two members for significant and critical portions of the field sampling phase of the project, and made attainment of the 300-home visit sampling goal more difficult.

The two-member field team continued, to the best of their ability, to deploy sampling equipment through the summer and into Fall 1994. In late November 1994, with the acknowledgement that the regional weather pattern had shifted to a winter regime of more unstable air masses passing through the study communities, field operations were curtailed.

4.1 References

Colome SD, AL Wilson, Yi Tian, California Residential Indoor Air Quality Study, Volume II, Carbon Monoxide and Air Exchange Rate: A Univariate and Multivariate Analysis. Sponsored by the Gas Research Institute, Pacific Gas and Electric Company, San Diego Gas and Electric Company, and Southern California Gas Company, (July 1994).

5. STUDY RESULTS

This section summarizes the field data collected in the performance of the residential study sampling project. Information gathered from the three surveys performed for each study home and the two home sampling visits is discussed in the appropriate sections. As was noted in an earlier section, no personal ozone sampling was performed in the course of the residential sampling study due to the lack of a validated and acceptable personal ozone sampler. In its absence, toolbox-sized timed exposure diffusion (TED) samplers were installed in and around study homes to document 24hr ozone concentrations.

The logistics of balancing available personnel resources, deploying a limited amount of sampling equipment, and successfully negotiating for residential access, resulted in a shortfall of sampling the desired number of originally targeted homes. Rather than achieving the originally targeted goal of sampling in 150 homes on two occasions, 126 homes were enrolled and studied.

Full-scale study field operations were initiated in February 1994 and continued into November 1994. During that time period, 247 home installations (126 first visits and 121 second visits) were completed. Of the 126 homes that participated in the project, 29 were located in the study community of Lake Gregory (LG), 37 were in Lancaster (LAN), 36 were in Riverside/Mira Loma (RIV/ML), and 24 were in San Dimas (SD). Of these 126 homes, 29 were documented as having evaporative (swamp) air cooling systems. Of the 247 home installations completed, 57 were completed in LG, 70 were from LAN, 72 were in RIV/ML, and 48 were in SD.

5.1 Survey Information

Survey information was available for 125 study homes. The three types of survey information (denoted as Baseline, Technician, and Follow-up) provided a means of documenting housing characteristics and mode of operation. Information provided by each of these survey approaches is provided in the following sections.

5.1.1 Baseline Questionnaire

Information from the Baseline Questionnaire (collected from participants in the Children's Health Study, or CHS students) was used to identify and stratify potential study homes. The questionnaire was collected during the 1993-94 school year, and home residents were contacted for possible residential study participation beginning in February 1994. From the CHS housing pool, 126 homes were eventually enrolled and studied during residential study field operations. The characteristics of those homes, as reported in the original Baseline questionnaire, are presented in this section. (In 10 cases where CHS students had moved since completion of the original Baseline Questionnaire, information from an update survey was used to replace obsolete information, and has been reported here as part of the baseline data set). A summary printout of the baseline questionnaire responses for the 125 homes providing survey information appears in Appendix A.

The baseline questionnaire data revealed that over 80% of the study homes were single family residences. (This percentage, which was based on partial data due to incomplete resident responses on the Baseline survey, increased to almost 90% when project field staff visited participating homes and completed Technician surveys - see Section 5.1.2). Single family homes dominated the study sampling pool in each of the four study communities, and in Lake Gregory, all participating homes were single family residences. Study homes across the four communities were comparable with regard to number of reported bedrooms, with three and four bedroom homes comprising over 70% of the study pool.

Some differences were observed in the age of the housing stock across community. The study sampling pool included more older homes in Riverside/Mira Loma and San Dimas than in Lake Gregory and Lancaster. Almost half of the homes studied in Lake Gregory and Lancaster were built in the 1980's or later, but fewer than 25% of the study homes in RIV/ML and SD had been built in the last 15 years. The study housing stock in RIV/ML was oldest, with 25% of the homes built in the 1950's. (Additional collected data supported the notion of older and smaller homes in the RIV/ML sub-group; house volume calculations, based on measurements made by project staff during home visits revealed that the average Riverside study home volume was

smaller than those in other communities [mean home volume results, in m³, by community - LG 419.9±153.4; LAN 335.5±131.2; RIV/ML 288.6±95.2; SD 379.6±141.5).

As has been previously discussed in the sampling considerations section of the report (Section 2.2.1), there were important differences in air conditioner availability in the study communities. In Lancaster, virtually every home had air conditioning (35/37), while in Lake Gregory, the distribution was completely reversed (with only 2/29 of the homes reporting having air conditioning). Central or room air conditioning accounted for over 50% of the homes in LAN, RIV/ML, and SD, and swamp coolers were reported in a substantial number of study homes (29% in LAN, 25% in RIV/ML, and 25% in SD).

The presence of a smoker in the study home was comparable across study communities. Reports of resident smokers varied from 11% in RIV/ML to 22% in SD, but accounting for non-resident smokers present in the home on a regular basis equalized study community smoking distributions (21% in LG, 27% in LAN, 19% in RIV/ML, 26% in SD).

5.1.2 Technician Survey

Technician surveys were completed by field personnel by a walk-through inspection of the study home during home visits for installation of sampling instrumentation. The survey form, and a summary printout of distributional results, is presented in Appendix B. The Technician survey may be divided into three broad areas of questioning: home construction (questions 1, 5, 6, and 7); odors (question 8); dust generation and control (questions 2, 3, 4, 9, 10, and 11). The housing survey discussion, with regard to information obtained from the Technician survey, is presented in the context of the 125 homes for which survey data was available.

5.1.2.1 Home Construction

Virtually all of the sampling homes (116/125) were single family residences, detached from other homes. (Three were mobile homes or trailers - one each in Lancaster, Riverside/Mira Loma, and San Dimas - and the remainder were either attached homes [such as townhouses or

condominiums] or multi-family dwellings [housing for 3-9 families]). About two-thirds (83/125) had attached garages.

Homes were three times as likely to be of concrete slab foundation, as opposed to raised floors with a crawlspace, except in Lake Gregory, where the ratio was reversed. When crawlspaces were noted, ventilated openings were always present (38/39 occurrences).

Ducted heating systems were present in 70% of the homes, and the return air handler was typically routed through an interior wall (50 of 88 reported cases) or attic (18/88). The remaining homes reported ducting through the garage, outside the home (such as on the roof), or did not specify the ducting location.

5.1.2.2 Odors

A variety of odors were reported in a number of homes, with some community variation. Mold or mildew odors were reported in 20% of the homes overall, but were recorded more often in Lake Gregory (31% of LG homes) and Riverside/Mira Loma (33% of RIV/ML homes). Pet odors were reported in 30% of the 125 homes, with odors reported in 36% of the LAN and RIV/ML homes. Cigarette odor was slightly more common in Lake Gregory (24% of LG homes, compared to 17%, 14%, and 17% for LAN, RIV/ML, and SD homes, respectively). Formaldehyde odors were reported in 3 homes (one in LG and 2 in LAN).

5.1.2.3 Dust Generation and Control

Most of the study homes were located in neighborhood settings, removed from major surface streets or freeways (110/125). Most homes were characterized by the presence of a dirt yard (107/125).

Almost 90% of the reporting homes used a doormat at the main entrance or at some entrance to the home, and doormat use was more frequent in Lake Gregory and San Dimas than in Riverside/Mira Loma and Lancaster.

Almost half of the main activity rooms (where sampling took place) in the home were carpeted, primarily by low nap carpeting covering the entire room.

Assessment of dust control in the sampling homes revealed a generally consistent pattern across communities, with half of the homes in each community rated in the "cluttered" to "lived in" categories (ratings 2 and 3 on a scale of cleanliness from 1 to 6, with 1 very cluttered with minimal or no attempt at dust control and 6 extremely meticulous dust control). No marked differences between communities were observed except in Riverside/Mira Loma, where twice as many homes as elsewhere (25% of the RIV/ML homes compared to 9-14% in the other three communities) were rated as having excellent cleaning (equivalent to 5 on a 1-6 scoring scale).

An attempt to quantify the amount of absorptive surface area in the ozone monitor sampling room of the home did not reveal any insights; 113/125 homes were rated as having an average amount of window covering and a majority of carpeted rooms, and there was no substantive variation in response across community.

5.1.3 Follow-Up Survey

Documentation of characteristic housing indices during the 24hr sampling period (such as use of air conditioning or heating, or the presence of a smoker in the house) was obtained by interview with the resident immediately following the sampling period. In this context, each visit to a sampling home may be considered a unique sampling event independent of other visits to the same home. Accordingly, the follow-up survey results are discussed in terms of the 246 home visits performed (125 first visits and 121 second visits). The summarized tabulation of resident responses on the survey appear in Appendix C, but are reviewed below.

While samplers were operating in the home, about a third of the residents (distributed uniformly across communities) reported performing some household cleaning activities (such as vacuuming and dusting). Home gardening and mowing were performed at about 10% of the

study homes during sampling. Virtually no one reported burning leaves (8/246, of which 5 instances were in LG and 3 were in RIV/ML).

Approximately one-fourth of the study homes used their heating during sampling (64/246), and of these, almost 40% (25/64) were in LG. Heating was primarily by forced air units, with some wall furnaces and a small number (5 reported cases) of fireplaces. Almost a third of the study homes (72/246) reported using air conditioning during sampling, and of these, almost half (32/72) were in LAN. Air conditioning used was reported to be central air about twice as often as window/wall units, and the central air units in use were predominately (38/48) refrigeration-type units rather than evaporative. Units were set about half of the time (26/48) to recirculate indoor air and about half to bring in outside air.

The use of virtually no other air treatment device, such as ionizers, humidifiers, dehumidifiers, filters, kerosene heaters, and wood stoves, was reported (that is, between zero and two cases of each of the above were reported). Where fans were reported in home use, they tended to be portable (69/246) or ceiling (76/246) units, rather than window, house, or attic fans (less than 4 to 8 reported cases each). When some sort of air handler was reported used (such as heating, air conditioning, or fans), usage typically was reported for several hours (at least 3 to 5 hours), and often much of the 24hr sampling period.

Over a third of the study homes (90/246) reported having a window open all of the time, and an additional half of all homes sampled (124/246) opened doors and windows for more than a few minutes during the sampling period. The amount of time that windows were left open was typically measured in hours rather than minutes, and the distribution of time reported with windows open did not strikingly vary across study community, except in SD; in LG, LAN, and RIV/ML, approximately 20% of the homes reported leaving windows for more than 3 hours during the afternoon of the sampling day (1200 to 1800 hours), whereas in SD, 6% reported open windows during the same sampling period. Several other pollution-generating activities in the home were also documented. Cigarette smoking during the 24hr home sampling period was reported less frequently (5/57) in LG homes than in other communities (16/70 in LAN, 13/72 in RIV/ML, 10/47 in SD). Other sources of smoke in the home (such as from incense or burning candles) were reported in 40/246 homes, distributed roughly equally across communities. About a third of the study homes (75/246) reported starting or running an automobile in an attached garage during the sampling period. Stove or oven usage was reported in 204/246 homes studied, with 96 of the study sites using the stove or oven for 60 minutes or longer. Only one home reported using the stove or oven for home heating, although there were ten recorded instances (during the 246 home visits) of residents reporting stove or oven usage during the 24hr sampling period for 240 minutes (4 hours) or more. (Closer examination of these ten survey responses revealed no apparent discrepancies or contradictions; wording of the question allowed for stove-top use - such as for heating water or coffee - to be reported in this category, and on two sampling instances, the resident interviewed reported keeping a pot of water boiling [for making coffee] for most hours of the day).

Over half of the reporting homes (163/246) used a clothes dryer during the sampling period, and 121 of these reported using the dryer for 1hr or longer. Seven homes reported that the dryer was vented into the home. Fourteen homes reported removal of shoes at the door (8 reported this was always done), and 50 homes reported there had been a major remodel in the home in the past year.

5.2 Exposure Assessment

The following sections summarize and describe the air monitoring results collected in the course of field operations. A tabular summary of the type and number of air monitoring samples collected during the study is presented in Table 5-1.

5.2.1 Ozone

5.2.1.1 Overview of TEDS samples

A total of 481 samples were reported for the residential TEDS measurements, 241 indoor and 240 outdoor. The results of these measurements are summarized in Table 5-2, which summarizes observed air monitoring results' means, standard deviations, and extreme value range, and Table 5-3, which presents percentile values for the monitored pollutants. A substantial number of the collected in-home ozone samples were below the calculated limit of detection of five parts per billion (5 ppb); this somewhat skewed the distribution. Due to the necessary subtraction of background (blank) values from some very low sample concentrations, a few measurements were calculated to be technically less than zero. A lower limit of detection constraint (using 5 ppb as the ozone LOD) was applied to subsequent statistical analyses. (The effect on models of ozone levels in the study homes caused by replacing minimal ozone values with the LOD value, a value of zero, or by any value between zero and the LOD, was negligible; these results are discussed in Section 6.1.1.1). The ozone data distributions are displayed in Figure 5.2-1 in a "Box and Whisker" plot and in Figures 5.2-2 through 5.2-4, where the distributions are presented in histogram form separately for indoor, outdoor and indoor/outdoor concentration ratios.

5.2.1.1.1 Univariate comparisons

5.2.1.1.1.1 Indoor vs. outdoor ozone concentrations

Indoor ozone measurements were almost always below the concentration of the outdoor measurements. Figure 5.2-5 is a scatterplot of the indoor and outdoor measurements. Out of over 200 sample sets collected (a set being both an indoor and outdoor sample), two were observed to have an indoor O_3 measurement higher than the simultaneously-collected outdoor sample. Of these two sample sets, only one of these involved a measurement in which the indoor value (53 ppb O_3) was substantially higher than the outdoor ozone concentration (36 ppb O_3).

The other case involved a measurement pair of very low concentrations, with the observed indoor level reported to be 4 ppb O_3 and the outside 3 ppb; this was interpreted as measurement noise by investigators. Review of the field records and photographs from the specific study residence in question (i.e., where the outdoor and indoor O_3 levels were 53 and 36 ppb, respectively) indicated that the inlet for the outdoor monitor may have been shielded by plant vines in front of the patio where outdoor monitoring took place. This might explain why this single sample was an outlier on the scatterplot. Figure 5.2-5 gives a good indication of the relation between indoor and outdoor ozone and of the variation in indoor/outdoor ratios (with percentile values for indoor/outdoor ratios presented in Table 5-3). In the absence of any notable indoor sources, low outdoor ozone concentrations coincided with uniformly low indoor concentrations. However, high outdoor concentrations led to a range of observed indoor O_3 concentrations, depending on a number of housing factors (see Section 6 for a presentation of modeling based on the collected data set).

5.2.1.1.1.2 Ozone by season and community

Based on historical patterns, the highest ambient ozone concentrations are expected between June and mid-September. This pattern was observed at the residential sites in the four communities. Figure 5.2-6 shows the outdoor ozone concentrations at the residences for the duration of the study. The four communities are shown separately, and they followed similar temporal patterns. In Figure 5.2-7, a similar plot is presented for the indoor measurements. A distinct seasonal pattern for ozone concentrations was also observed inside homes with higher concentrations occurring during the summer months.

A seasonal pattern for indoor/outdoor ratios was also investigated. Indoor/outdoor ratios tended to be greater during the higher ozone summer period (see Figure 5.2-8). In other words, when outdoor ozone levels were high, the proportional indoor exposures also tended to be higher. Originally, we had expected the use of air conditioning during the hotter summer months to lower the overall indoor/outdoor ratio during these months. Questionnaire data, however, indicated that air conditioning use tended to be limited and occurred only during the warmest days of the year.

At other times, the occupants in these Southern California communities were inclined to use natural ventilation, which tended to increase indoor/outdoor ratios.

A summary of the collected ozone observations, for both indoor and outdoor sampling, in each of the four study communities is presented in Table 5-4. Caution should be taken to avoid over-interpretation of the presented data; community comparisons may not be appropriate, given that sampling was not performed in each community simultaneously. No striking differences were apparent across the four communities studied with regard to indoor or outdoor ozone levels, or with the ratio of the two measurements. In-home concentrations varied from about 0.01 ppm in San Dimas homes to 0.017 ppm in Lake Gregory homes. Outdoor levels ranged from 0.027 ppm O_3 in the San Dimas homes monitored to 0.045 ppm in Lake Gregory. The ratio between indoor and outdoor ozone varied from 0.33 in Lancaster to 0.41 in San Dimas.

5.2.1.1.1.3 Ozone by home air conditioning type

To evaluate the potential importance of home air conditioning type on observed ozone levels in the home, analyses were performed with the data set divided into homes with no reported air conditioning (no A/C), homes reporting the presence of a central or room air conditioner unit (Central or Room A/C), homes reporting the presence of a swamp cooler unit (Swamp Cooler Only), and homes reporting the presence of both swamp cooling and central or room air conditioning units (Swamp + Central or room A/C). Table 5-5 summarizes the residential sampling data, by reported air conditioning type, for ozone. Homes with "Central or Room A/C" tended to have lower indoor ozone levels than other homes (0.009 ppm O₃ compared to 0.016 to 0.020 ppm O₃ in other home types), but there was considerable data overlap (standard deviations were equivalent to the reported averages). Observed outdoor ozone concentrations were not markedly different, when homes were divided in the above manner.

Indoor/outdoor ratios for homes with swamp coolers present tended to be slightly higher than other homes (0.46 compared to 0.32 to 0.37), but overlapping data prevented this from becoming a difference of statistical significance.

5.2.1.1.2 Distributional plots

Since air quality data frequently follow approximately log normal distributions, log-probability plots were prepared for the collected data. The first of these plots are presented in Figure 5.2-9 for the indoor and outdoor ozone measurements by TED sampler. The upper portions of the distributions appeared to be log normal, but the lower concentrations were not, possibly due to the values approaching the lower limit of sampler detection (5 ppb). Figure 5.2-10 presents results for the indoor/outdoor ratios on a log-probability plot.

5.2.1.1.3 Data quality summary

Because of the primary importance of ozone measurements to this study, the data quality results for the TEDS measurements are summarized in this section. Additional detail on these issues is contained in Section 3 and Appendix E, which discuss quality assurance and quality control for the project.

Table 5-6 presents the relative standard deviation (RSD) results for the 58 TED pairs that were collected at the residential sites. The mean RSD was 0.28 ppb. These values are shown in Figure 5.2-11 as a scatterplot of samples and duplicates. Most of the data pairs fell along the 1:1 line with an expected level of precision. Four of the data pairs were visual outliers to the generally good paired agreement, which was characteristic of this passive method. Variable blank values are a possible explanation for this infrequent rate of paired difference, as discussed in Appendix E.

5.2.1.2 Continuous ozone sampling

Continuous ozone samplers (commercial ultra-violet photometers, Model 1003-AH, Dasibi Environmental Corporation, Glendale CA) were deployed in a selection of homes to provide data for comparison with results from the TED sampler-based aggregate 24hr ozone samples (presented in the previous section) and to evaluate the dynamics of indoor and outdoor ozone concentrations. Information gathered from the continuous monitoring of indoor and outdoor ozone levels in a small number of study homes is presented in this section. Difficulties in field logistics (including the inconvenience to study participants, the cumbersome nature of transporting and setting up the monitors, and the need to maximize the total number of study homes sampled with the primary TED samplers) resulted in eight homes actually being outfitted for continuous indoor and outdoor ozone sampling. In three of the homes, either the indoor or the outdoor recording channels failed to collect real-time data. Accordingly, field data for five indoor/outdoor continuous 24hr traces were collected and are presented here.

5.2.1.2.1 Case studies

Of the five case studies, three homes contained evaporative swamp coolers, and two were equipped with refrigerant air conditioners. Continuous traces of indoor and outdoor ozone concentrations are plotted in this section; indoor and outdoor averages are presented, as are average indoor/outdoor ozone ratios. The traces tended to clearly show when conditions changed in the home, causing alteration in the indoor/outdoor ratios.

5.2.1.2.1.1 Swamp-cooled homes

Figure 5.2-12 presents the indoor and outdoor concentration trace for Home #15. During the sampling period, the integrated 24hr indoor average was 0.03 ppm, while the outdoor level was 0.04 ppm ozone. However, during the late afternoon, indoor O_3 concentrations (as well as outdoor levels) were in excess of the 0.09 ppm One Hour Ambient Air Quality Standard.

The average indoor/outdoor ratio of 0.67 in this home was one of the highest observed, and for several hours in the late afternoon and into the evening, the indoor/outdoor ratio was close to unity. The effect of the high air exchange rate is apparent with the indoor concentration closely following the outdoor concentration for much of the day. A rapid decrease in indoor ozone concentration was noted during the period between approximately 1300 and 1700 on 8/12/94 (see Figure 5.2-12). One potential explanation of this observation is intermittent fan cycling of the air conditioner unit. During the interim periods, only natural ventilation, as compared to any mechanically-assisted ventilation, would determine the exchange of air in the home, and thus account for the observed behavior.

The data also show a time lag between indoor and outdoor ozone level, as recorded by the continuous tracings, beginning at approximately 0930 on the morning of 8/12/94. Possible explanations for this lag include a home sealed from much indoor intrusion of outdoor air (or a home with sufficient surface sinks to quench ozone levels for a limited period of time). Based on the tracing, levels in the home did not start to climb for at least 90 minutes, until outdoor levels exceeded about 50 ppb ozone. At that point, the indoor rate of increase paralleled that of the outdoor ozone rise, until the cycling phenomena, as noted above, occurred.

Figure 5.2-13 presents data from a ducted swamp-cooled home with a relatively high indoor/outdoor ratio ("ducted" here refers to a swamp cooler connected by air handling ducts to several rooms in the home, as compared to a single supply register immediately adjacent to the swamp cooler unit). For this home, indoor ozone concentrations averaged 0.02 ppm during sampling, while the simultaneous outdoor level averaged 0.04 ppm. The indoor concentration tracked the outdoor for the entire sampling period with only a minimal time lag, and the average indoor/outdoor ratio for the sampling period was 0.49. During the two afternoons captured in the 24hr sampling period (since sampling in this home was initiated in mid-afternoon), observed hourly indoor/outdoor ratios approached 0.8 to 0.9 (see Figure 5.2-13).

During the morning of 9/11/94, a noticeable time lag developed between indoor and outdoor ozone levels. Where levels had tracked closely for much of the previous sampling time, beginning at about 0730, outdoor and indoor O_3 levels diverged, with indoor levels staying essentially zero until about 1000. At that time, the parallel tracking of indoor and outdoor levels resumed. Explanations for the observed morning time lag include the internal surface areas of the home (walls, carpets, furniture, and materials) acting as chemical sinks for the low levels of ozone present (outdoor levels during this time did not exceed 30 ppb), or a slow rate of air exchange with the outdoor environment due to home windows and doors being closed.

Results from the third and final swamp-cooled home sampled with continuous monitors appear in Figure 5.2-14. The indoor ozone concentration averaged 0.01 ppm and the outdoor level averaged 0.02 ppm. The averaged indoor/outdoor ratio was 0.34, which was lower than for

the other two swamp-cooled homes sampled. Indoor ozone in this home generally consistently tracked outdoor concentration, except at midnight during the sampling period, when an ambient midnight spike was observed in the outdoor tracing. This spike, which lasted for over 30 minutes, was not readily explainable by the collected information from the home, or by an evaluation of the immediate neighborhood around the residence.

5.2.1.2.1.2 Refrigerant air-conditioned homes

Figures 5.2-15 and 5.2-16 report data collected in homes containing refrigerant air conditioning, and demonstrate the influence of occupant activities on indoor/outdoor ratios for ozone. As Figure 5.2-15 illustrates, the indoor ozone concentration was initially a low percentage of the outdoor level recorded. Late in the evening, however, there was a dramatic change in recorded levels, and the indoor ozone values approached the outdoor concentration and closely tracked it until approximately 0800 the next day. After 0800, the indoor level declined significantly and remained considerably lower than the outdoor values observed. This pattern suggests that the air conditioning was off and windows were open during the evening, allowing indoor and outdoor levels to come into close agreement. When the windows were closed during the day, the indoor ozone levels slowly passed through the 30 to 40 ppb range, while outdoor levels steadily increased from 40 ppb to over 80 ppb.

An almost completely reversed pattern of window usage, and its resulting effect on indoor and outdoor variations in ozone concentration, is observable from the data depicted in Figure 5.2-16. In the home sampled, indoor concentrations were much lower than those outdoor during the late afternoon and started to approach the outdoor levels during the early evening. The windows were apparently closed around 2200 that evening, and indoor levels fell well below those outdoors and remain low for the duration of the sampling period.

On the following morning during rush hour traffic (from approximately 0630 till 0830, a downward spike appears in the outdoor ozone data tracing. One possible explanation for the duration and intensity of the observed depression in outdoor ozone levels is local ozone depletion by NOx scavenging, associated with rush hour traffic (or school-based traffic) or some other local

source of NOx.

5.2.1.2.2 Comparison with TED sampler data

One of the goals of conducting continuous ozone sampling in homes was to verify the results from the TED sampling conducted simultaneously in and around the study homes. Results from the five homes summarized above were combined with the other three homes that had either an indoor or an outdoor concentration recording to produce Figure 5.2-17. Most of the results fall on the 1:1 line, with the exception of two observations that are parallel to but off the line. These two points belong to the previously identified batch of Ogawa filter blanks (Batch #8) that were found to have been variable and generally high (and is discussed in Appendix E). The apparent source for the abnormally large and variable background levels found among samples in this batch lies in the handling and preparation procedures performed in the HSPH laboratory at Harvard, the source of all Ogawa filters used in the study. With the Batch #8 filters removed, the correlation coefficient between the TED and continuous monitoring results, integrated over the same time period, was 0.95. With the constant set to zero, the regression coefficient was 0.94, indicating good agreement between results from the TED sampling and continuous monitoring approaches.

The periodic occurrence of variable Ogawa filter batches is a previously recognized problem in the HSPH laboratory (K. Anderson, private communication, 1994). While the effective solution would appear to be quality control sampling of selected filters during the preparation procedure in the HSPH laboratory, this approach will more likely need to be the responsibility of the end user prior to deployment of filters for field sampling.

5.2.2 Particles

Particle samples were taken for aerodynamic size cutoffs of 2.5 and 10 micrometers. During the first few months of routine field operations (February through May 1994), particle sampling was performed using glass fiber filters. This was a poor sampling choice, due to filter media fragility. Although use of glass fiber filters in the PEM impactors was in conformance with manufacturer's recommendations, use of glass fiber filters was contrary to the project's standard operating procedures, which specified teflon filters. As previously discussed, glass fiber filters were found to be inadequate for sampling, since they were often cut by the sharp edge of the filter holder used in this study. In late June 1994, we subsequently shifted sampling to teflon filters with a protective olefin outer ring, which prevented filter loss at the perimeter of the filter. Due to the unpredictable nature of the filter loss from the fiber filters, results are presented only for the teflon filter-based data set. Results are presented first for the $PM_{2.5}$ inlets and next for the PM_{10} inlets.

It should be noted that in all PM mass calculations, a nominal sampling pump flow rate of 4 liters per minute was used to determine sampling air volumes. This practice could have resulted in an underestimate of the true PM concentrations present at the time of sample collection.

5.2.2.1 PM_{2.5}

A total of 132 $PM_{2.5}$ samples (67 indoor and 65 outdoor) were collected. The results of the $PM_{2.5}$ measurements are summarized in Tables 5-2 and 5-3. Indoor $PM_{2.5}$ concentrations tended to be slightly higher than those outdoors (median percentile value 1.10, inter-quartile range 0.84 to 1.68), suggesting the presence of fine particle sources inside many of the sampling homes. The indoor and outdoor differences in $PM_{2.5}$ concentration distributions are shown visually in "Box and Whisker" plots in Figure 5.2-18. The data collected identified several homes with substantial indoor levels of $PM_{2.5}$ sources of particles indoors. This result can be observed in the extended tail of the indoor histogram compared with the outdoor values, as presented in Figures 5.2-19 and 20. The histogram of indoor/outdoor ratios (Figure 5.2-21) showed that most homes had indoor to outdoor $PM_{2.5}$ ratios less than 1.5, but that a few homes had ratios of 2 to 20. As Figure 5.2-22 shows, many of the homes in which high $PM_{2.5}$ levels (indoor $PM_{2.5}$ greater than 40 µg/m³) were observed were homes at which outdoor $PM_{2.5}$ levels were lower than 40 µg/m³.

The sources and nature of the indoor levels in these homes, in which the occupants were subjected to elevated particle concentrations, is beyond the scope of the present study, but of potential future study interest.

5.2.2.1.1 Indoor-outdoor PM_{2.5} relations

Indoor particle concentrations appeared to be related to outdoor concentrations for a large fraction of homes. Figure 5.2-22 shows that when outdoor concentrations were high, the concurrent indoor concentrations were often elevated as well. This scatterplot also makes it clear that indoor sources may dominate and cause the indoor concentrations to be substantially in excess of the corresponding outdoor concentrations.

5.2.2.1.2 Temporal patterns of PM_{2.5}

Seasonal patterns for $PM_{2.5}$ concentrations were less apparent than for ozone in this data set. Elevated outdoor particle concentrations (see Figure 5.2-23) occurred during specific time periods without an obvious seasonal trend. The collected data suggested, but did not clearly demonstrate, the presence of higher indoor concentrations during the fall (see Figure 5.2-24, which plots the indoor time trace). As shown in Figure 5.2-25, the indoor/outdoor ratios for $PM_{2.5}$ suggested a seasonal pattern, with ratios in several homes during October sampling higher than at other times of the year. One potential explanation for this study's failure to detect a seasonal pattern for outdoor and indoor $PM_{2.5}$ is that this study did not sample during midwinter, when the highest ambient concentrations of particles are historically encountered in the sampling region, and when homes may have lower air exchange rates (by keeping windows closed to maintain indoor temperatures at comfortable levels).

5.2.2.1.3 $PM_{2.5}$ by community

A summary of the collected $PM_{2.5}$ data, by community, appears in Table 5-7. A small number of observations (less than 23 in each community) and acknowledgement that sampling was not performed simultaneously across study communities (since simultaneous sampling was not a consideration in the exposure design or protocol) should limit generalizations drawn from the data.

The community-specific $PM_{2.5}$ data suggested that indoor levels were lower in Lake Gregory homes than in Riverside/Mira Loma homes. However, the Riverside/Mira Loma data may have been skewed by the presence of one smoking home (House ID #69), in which 106 μ g/m³ PM_{2.5}

was measured (and a reported 40 cigarettes were smoked during the 24hr sampling period). The $PM_{2.5}$ measurement in that home was significantly higher than other maximum values observed in other communities. Conversely, outdoor levels were also observed to be higher in the Riverside/Mira Loma community (in agreement with historical air monitoring data) than in other communities, and outside the Home #69, $PM_{2.5}$ was measured at almost 77 µg/m³, which was also the highest outdoor $PM_{2.5}$ value observed.

The data suggested that homes in the Lake Gregory and Lancaster areas had higher indoor/outdoor $PM_{2.5}$ ratios than their counterparts in the Riverside/Mira Loma and San Dimas communities, but a limited number of samples for comparison necessarily limit generalizations from these observations.

5.2.2.1.4 PM_{2.5} by home air conditioning type

A summary of the $PM_{2.5}$ data by home air conditioning type is presented in Table 5-8. Observed indoor $PM_{2.5}$ levels tended to be slightly higher in "Swamp Cooler Only" homes (25 $\mu g/m^3$, compared to 12 to 20 $\mu g/m^3$ in other home air conditioning types), but small sample sizes, and the likely confounding of air conditioning type with community location (since many of the swamp-cooled homes were in Lancaster, and none were in Lake Gregory) limit the data interpretation. Mean indoor/outdoor $PM_{2.5}$ ratios across air conditioning type varied from 1.57 to 2.31, but the higher ratios were driven by only a few extreme homes (in which I/O ratios were 11 or greater). Given the range of data and the analytical limitations stated above, no important differences were observable in the $PM_{2.5}$ data analyzed by home air conditioner type.

5.2.2.1.5 Distributional plots

Figure 5.2-26 presents the indoor and outdoor distributions for $PM_{2.5}$ on a log-probability plot. This figure indicates that both the indoor and outdoor distributions were approximately log normal. The indoor concentrations tended to be higher than the outdoor concentrations over the entire distribution. Figure 5.2-27 gives the log-probability plot for the individual indoor/outdoor ratios calculated at the residences. This distribution was approximately log normal until the 75th to 80th percentile, where it became discontinuous. These higher ratios were likely due to cigarette smoke or some other source of high particle concentration in the home.

5.2.2.2 PM₁₀

A total of 178 PM10 samples (88 indoor and 90 outdoor) were reported. The results of the PM_{10} measurements and the indoor/outdoor ratios calculated for the homes are summarized in Tables 5-2 and 5-3. Similar to the results for $PM_{2,5}$, indoor PM_{10} concentrations tended to be slightly higher than the outdoor concentrations in this set of homes (median percentile value of 33 µg/m³ compared to 29 µg/m³, respectively) indicating the presence of PM_{10} sources inside a subset of the residences. The mean indoor/outdoor (I/O) ratio for PM_{10} was 1.54, and the observed median I/O ratio for PM_{10} was 1.05 (with an inter-quartile range from 0.66 to 1.86). The observation that the median indoor/outdoor PM_{10} ratio was 1.05 suggests that although several homes had strong indoor PM_{10} source contributions, at many other homes, indoor levels were very close to those observed outside the home. This suggests that indoor PM_{10} levels might be largely governed by ambient concentrations in a significant portion of our study homes. However, the gravimetric analyses performed in this investigation are insufficient to provide convincing evidence on this matter; chemical analysis and source apportionment approaches would be needed to clarify this situation.

The indoor and outdoor differences in PM_{10} concentration are shown visually in the "Box and Whisker" plots in Figures 5.2-28. These figures indicate greater similarity between indoor and outdoor samples than were observed in the $PM_{2.5}$ sampling results. This observation suggests that the impact of indoor combustion sources is better identified with $PM_{2.5}$ measurements.

Figures 5.2-29 and 30 show the outdoor and indoor histograms, respectively, for the PM_{10} sample results. Three indoor samples approaching $300 \,\mu g/m^3$ were collected. The histogram of indoor/outdoor ratios (see Figure 5.2-31) revealed that most homes had I/O ratios lower than approximately 1.5, with a few homes indicating the presence of strong indoor sources.

5.2.2.2.1 Indoor-outdoor PM10 relations

The indoor-outdoor scatterplot presented as Figure 5.2-32 shows that the majority of homes had indoor PM_{10} concentrations that roughly followed (and did not depart substantially) from the outdoor ambient concentrations. However, a handful of homes did exhibit high indoor concentrations (reflective of strong indoor sources) that substantially exceeded the ambient concentrations measured outside the residence.

5.2.2.2.2 Temporal patterns of PM₁₀

As was the case with the collected $PM_{2.5}$ data, no clear seasonality was observed in the outdoor or indoor PM_{10} concentrations (see Figures 5.2-33 and 34). Several measurements made during late October 1994 produced some of the highest observed indoor and outdoor concentrations, but field sampling was not continued through the winter months (when elevated levels of PM are historically observed). As Figure 5.2-35 shows, the samples collected in late October were not the highest indoor/outdoor ratios observed; these were scattered throughout the study period.

5.2.2.2.3 PM₁₀ by community

A summary of the PM_{10} sampling results, by community, is presented in Table 5-9. As was the case with the $PM_{2.5}$ data, homes in the Riverside/Mira Loma community were observed to have higher indoor and higher outdoor PM_{10} levels, compared to homes in the other three study areas. (This appeared to be the case, even after taking into account that the highest indoor PM_{10} measurement, 294 µg/m³, was collected in a smoking home in Riverside/Mira Loma). Homes in the Lake Gregory area tended to have lower indoor and outdoor PM_{10} levels than the other study communities, but these observations should be considered preliminary, since only a small number of PM_{10} sampling data (less than 27 samples in each community) was available from each study area.

Communities directly downwind of Los Angeles (Riverside/Mira Loma and San Dimas) had lower indoor/outdoor PM_{10} ratios than those communities in the high desert (Lancaster) or up in the mountains (Lake Gregory).
5.2.2.4 PM_{10} by home air conditioning type

The results of PM_{10} analyses by reported home air conditioning type are summarized in Table 5-10. Homes with swamp coolers appeared to have higher indoor PM_{10} levels, but caution should be taken to avoid over-interpretation of the available data. There were a small number of samples in each of the sub-categories, limiting the conclusions that could be drawn from these analyses. Secondly, there was one very high PM_{10} sample measured among the six "Swamp Cooler Only" homes (294 μ g/m³), which skewed the reported mean for this sub-category. Finally, sampling results from swamp-cooled homes may be partially confounded by the community bias introduced by categorizing homes in this manner, since no swamp-cooled homes were located or sampled in the Lake Gregory (a high ozone, high particle community, based on historical and experimental design information), and a large number of swamp-cooled homes were located in Lancaster (a high ozone, high particle community, based on historical and experimental design information).

No firm conclusions could be drawn from the comparative indoor/outdoor ratio data for these sub-categories, due to data overlap and a small number of samples after sub-categorization. However, the data suggested that homes with no reported air conditioning had higher indoor/outdoor PM_{10} ratios than those homes with central of room air conditioning (2.08 vs. 1.16). This may reflect some particle-capture efficiency of central or room air conditioning, or reflect some inertial impaction of particles in homes served by active mechanical movement of the indoor air.

5.2.2.5 Distributional plots

Log-probability plots for indoor and outdoor PM_{10} are presented in Figure 5.2-36. Indoor and outdoor distributions of PM_{10} were approximately log normal, and the indoor concentration distribution was generally slightly higher than the outdoor distribution. This difference was less striking than that observed in the $PM_{2.5}$ sample set. The log-probability plot of the PM_{10} ratios is presented in Figure 5.2-37. Approximately log normal behavior was observed from the 5th to the 95th percentile across the distribution. The five homes represented above the 95th percentile were observed to have I/O PM_{10} ratios significantly higher than the other study homes.

The explanation for this apparent discontinuity may relate to inherent distributional instability at high percentile values or to actual processes occurring in residential locations exhibiting higher indoor concentrations; the relatively few observations at this high end of the distribution provide insufficient data to address this issue.

5.2.2.2.6 Data quality summary

Duplicate results for the particle samples are summarized in Table 5-6, which shows the relative standard deviation to be $0.18 \,\mu g/m^3$. This agreement is graphically shown in Figure 5.2-38. The observed precision was good over the range of duplicate observations, from a few $\mu g/m^3$ to 141 $\mu g/m^3$. The residual plot for the regression of the samples and duplicates is presented in Figure 5.2-39, and reports that duplicate measurements were within approximately 15 $\mu g/m^3$ of one another.

5.2.2.3 Collocated PM₁₀ and PM_{2.5} Sampling

The planned study design included the deployment of collocated PM_{10} and $PM_{2.5}$ samplers in 25 study homes, to allow comparisons of residential PM by size fraction. Collocated PM_{10} and $PM_{2.5}$ sampling was successfully performed during 23 home visits. A summary of the collected information appears in Table 5-11.

Outside the study homes, measured PM_{10} values ranged from 5 to 114 µg/m³, while $PM_{2.5}$ levels from 2 to 77 µg/m³ were observed. As expected, PM_{10} always exceeded $PM_{2.5}$, except outside one home where levels were very low (Home #147, where PM_{10} was measured at 11 µg/m³ and $PM_{2.5}$ was measured at 17 µg/m³). No apparent reason for the discrepancy was readily assignable, based on a review of the collected questionnaire data and photographs of the sampling site.

Indoor PM values ranged from 2 to 162 μ g/m³ for PM₁₀, and from 4 to 107 μ g/m³ for PM_{2.5}. PM_{2.5} values were usually less than PM₁₀, with one notable exception. In Home #130, in which the heaviest cigarette usage was reported (50 cigarettes smoked during the 24hr sampling period), measured PM_{2.5} levels were twice as high as indoor PM₁₀ concentrations measured in side-by-side PM samplers (86 μ g/m³ compared to 47 μ g/m³, respectively). Several types of air modifying equipment were used in this home during the sampling period (including a gas wall furnace for heating, an evaporative air conditioner, and a ceiling fan), but no clear relationship between the observed values and recorded home operations could be made. During an earlier visit to this home for sampling, 20 cigarettes per day had been reportedly smoked, and observed PM_{2.5} and PM₁₀ levels of 20 μ g/m³ and 45 μ g/m³, respectively, had been measured. This might suggest that the PM_{2.5} reading of 86 μ g/m³ might be suspect, but cigarette usage (a source of fine particles) during the sampling period was very high (50 cigarettes reported smoked), lending credibility to an expectation of elevated PM_{2.5} levels. Upon review of the data, no scientific or objective rationale for invalidating either of the PM measurements, in and of themselves, could be found. Accordingly, since no methodological errors could be found, the decision was made by investigators to include the data in the reported data set.

The collected information and previous research by other investigators (Wallace, 1996) clearly identified smoking as a critical influence on indoor PM levels (see modeling results in Section 6). Since seven collocated PM_{10} and $PM_{2.5}$ samples were collected in homes in which smoking was reported during sampling, the collected samples were considered separately (as subsets of smoking and non-smoking homes) to learn more about the relationship between PM_{10} and $PM_{2.5}$.

Figure 5.2-40 graphically presents the collocated PM_{10} and $PM_{2.5}$ data obtained from nonsmoking homes during the study. Although the sample size was quite small (n=15), correlation values were determined for the collected data. The correlation value in non-smoking homes sampled for collocated outdoor PM_{10} and outdoor $PM_{2.5}$ was 0.86, possibly reflecting a homogeneous mix of regional (and not specific localized) PM sources. The correlation value in non-smoking homes sampled for collocated indoor PM_{10} and indoor $PM_{2.5}$ was 0.40, and likely represented a multitude of specific and varying indoor sources in the sampling homes.

For comparative and qualitative purposes, a similar examination of the collocated PM sampling was performed in smoking homes. The results for the seven collocated PM samples in smoking homes are illustrated in Figure 5.2-41. The calculated correlation values associated

with collocated outdoor PM_{10} and $PM_{2.5}$ in smoking homes was 0.86, and in smoking homes with collocated indoor PM_{10} and $PM_{2.5}$ was 0.77. As the figure illustrates, these correlations were clearly driven by single extreme points and a small number of data points, so care should be taken to avoid over-interpretation.

5.2.3 Formaldehyde

5.2.3.1 Overview of formaldehyde samples

Formaldehyde was monitored in a subset of homes (117 measurements reported, divided as 99 indoor and 18 outdoor), based on a previously described sampling approach. Since indoor sources of formaldehyde are ubiquitous and indoor concentrations are known to generally exceed outdoor concentrations, only a subset of homes were monitored simultaneously for indoor and outdoor formaldehyde concentrations. Tables 5-2 and 5-3 summarize the study findings with regard to formaldehyde measurements in and around the study homes.

As expected, indoor concentrations dramatically exceeded outdoor ambient levels (see the "Box and Whisker" plots on Figure 5.2-42 in which the 95th percentile value outside is lower than the mean and median concentrations inside). Figures 5.2-43 and 5.2-44 present the histograms for outdoor and indoor distributions, respectively. The histogram of I/O ratios in Figure 5.2-45 showed that most indoor concentrations exceeded outdoor values. The median I/O ratio for formaldehyde observed was 3.75, with an inter-quartile range from 1.98 to 7.38 (see summary values in Table 5-3).

5.2.3.2 Univariate comparisons

5.2.3.2.1 Indoor vs. outdoor formaldehyde concentrations

As described in the study design, formaldehyde sampling was designated as a lower study priority than ozone or particle sampling, and sampling was preferentially assigned to indoor locations. This resulted in a relatively small data set (18 joint measurements) of simultaneous indoor and outdoor formaldehyde. Despite the small data size, it was apparent that indoor sources had a dominant influence on formaldehyde concentrations (see Figure 5.2-46).

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5.2.3.2.2 Formaldehyde by season

Figures 5.2-47 and 5.2-48 display the time plots for outdoor and indoor formaldehyde measurements, respectively. There was no clear seasonal pattern to either trace. Similarly, no clear seasonal pattern was observable in the I/O ratio data set (presented in Figure 5.2-49).

5.2.3.2.3 Formaldehyde by community

Table 5-12 summarizes the formaldehyde sampling results by community. As described previously, indoor values were very low in all communities. There was some suggestion in the data that homes in the Riverside/Mira Loma area had slightly higher indoor formaldehyde concentrations than in the other three study communities (an average value of almost 15 μ g/m³, compared to values of 9 to 10 μ g/m³), but there was also considerable overlap in concentration distributions across communities.

Outdoors, only a handful of data were collected in any given community, so that any generalizations regarding indoor/outdoor formaldehyde ratios seem unwarranted.

5.2.3.2.4 Formaldehyde by reported home air conditioning type

The formaldehyde sampling results, categorized by reported air conditioning type, is reported in Table 5-13. Indoors, formaldehyde levels were low and not markedly different across air conditioning types, ranging from 9 μ g/m³ in homes without air conditioning to 13 μ g/m³ in homes with central or room air conditioning. A small number of outdoor formaldehyde measurements made interpretation of indoor/outdoor ratios ambiguous.

5.2.3.3 Distributional plots

The log-probability plot for indoor formaldehyde is presented in Figure 5.2-50 and followed an approximate log normal pattern for concentrations above approximately 2 $\mu g/m^3$. As described above, data on I/O ratios was limited, but the log-probability plot for these ratios is presented in Figure 5.2-51. The collected data showed an approximately log normal pattern in spite of the low number of data pairs.

5.2.3.4 Data quality summary

Five data pairs were collected during formaldehyde collocated sampling. Limitations in the availability of field monitoring equipment prevented collection of a larger set of duplicate samples. However, previous experience with this method has demonstrated excellent precision and accuracy. The method precision was reinforced with the results from the small subset of duplicate samples. Table 5-6 summarizes the precision data and indicates a relative standard deviation of less than $0.09 \,\mu g/m^3$. The scatterplot of duplicate measurements, shown as Figure 5.2-52, revealed little departure of samples and duplicates from the 1:1 line.

5.2.4 Air Exchange Rates

5.2.4.1 Overview of air exchange rate measurements

A total of 161 measurements were made to determine residential air exchange rates. These data are presented using two approaches. The traditional approach calculates home volume by measuring wall-to-wall volume without accounting for furniture and other space-occupying objects. As an exploratory approach, the volume of space-occupying objects (such as furniture, closets, and cabinetry) were estimated and subtracted from the exchangeable volume. Use of the corrected volume tended to increase the estimates of air exchange rate by approximately 10% and appeared relatively constant from house to house in this sample.

Tables 5-2 and 5-3 provide descriptive statistics for these measurements. Figure 5.2-53 shows "Box and Whisker" plots for the corrected and traditional air exchange rate (AER) distributions. The distribution of AER values is shown in histogram form in Figure 5.2-54. There was greater confidence in AER values less than 1 hr⁻¹, since higher AER values encounter the limits of detection for this method as deployed.

5.2.4.2 Corrected vs. raw AER

Figure 5.2-55 presents the scatterplot of corrected vs. traditional AER calculations. This plot suggests that factors other than estimated residential contents accounted for the observed variation

in air exchange. Originally, we had anticipated that the fraction of home volume occupied by "objects" would be more variable than these data suggest for this set of homes. The narrowness of this relationship is illustrated in Figure 5.2-56, which shows that the ratio of traditional to corrected air exchange varied over the narrow range of 90-100%. The consistency of this relationship suggests that measurement of furniture and cabinetry in homes, to provide corrected AER calculations, is unnecessary.

5.2.4.3 Home volume vs. AER

Figure 5.2-57 shows the relation between home volume and estimated air exchange. In addition to the x and y axes in the plot, an effective boundary was observed at the volume vs. 1/volume curve in the upper right quadrant defined by the limits of detection of this method. The limits of detection for this method are dependent on the emission of perfluorocarbon tracer and the volume into which it is diluted, and the figure identifies the boundary above which AER can not be determined.

5.2.4.4 Home volumes

One of the more time consuming requirements for the technicians in this study was determination of the residential volumes, which were required for calculation of air exchange rates. The deployment of perfluorocarbon sources, and the measurement of home volume, required an additional visit to each residence, separate from the actual pollutant sampler instrumentation installation and collection effort. One of the useful results of this effort is information on residential volumes. Figure 5.2-58 present a scatterplot of corrected and whole house volume, expressed in liters. The tight relationship between corrected and conventional AER is a reflection of the level of agreement observed for the two volume measurements.

5.2.4.5 AER by season

Figure 5.2-59 shows the time plots for air exchange during the study. Although field measurements were not made during the winter period between December and February, there was evidence of a seasonal AER pattern. Air exchange rates were lower during the spring and fall periods when compared with samples collected during the summer. Summertime sampling

was also characterized by a much more variable pattern of air exchange. While air conditioning will generally reduce air exchange rates, there was no evidence in this data set that overall summertime air exchange rates were reduced as a result of air conditioning use in this region of the country.

5.2.4.6 AER by community

A summary of air exchange rate data by community is reported in Table 5-14. Community AER averages were all in the 0.7 to 0.8 per hour range. with only a slight hint that homes in Lake Gregory might have had marginally higher AERs.

5.2.4.7 AER by reported home air conditioning type

Table 5-15 presents the AER data by reported home air conditioning type. AER measurements in "Swamp Cooler Only" homes (1.2 hr^{-1}) were higher than in homes reporting the presence of a central or room air conditioner (0.6 hr^{-1}) , or in homes reported no air conditioning (0.9 hr^{-1}) . This is not surprising, since swamp coolers operate by delivering high volumes of outdoor air, through water-soaked fiber filters, to the indoor environment.

5.2.4.8 Distributional plots

The log-probability plots for air exchange rates and home volumes are presented in Figures 5.2-60 and 5.2-61, respectively. Corrected and traditional distributions are shown for each measure and reinforce the similarity of these approaches. Both distributions were approximately log normal over the entire range of observations except for the extreme tails.

5.2.5 Fine Particulate Matter and Vapor-Phase Acids

Two-Week Samplers (TWS) were deployed in and around twelve homes for two-week periods beginning in mid-August 1994 and continuing into November 1994. Due to instrumentation logistic requirements and investigator concern that installation of the TWS in a study home might discourage residents from continued study participation, the two-week study sampling periods for the TWS pilot effort were typically conducted after completion of the second study visit to the home. Two homes in the same community were studied during each of the sampling periods. Homes were selected based on resident approval for study access and to provide a sampling selection across the four study communities. Homes were not selected based on any preestablished hypothesis or test criteria because of the pilot nature of the sampling. Performance specifications details regarding development of the TWS have been presented previously (Lurmann et al 1994).

Samplers were deployed in and around homes according to the same siting criteria used for the deployment of other sampling instrumentation used in the residential sampling study. Indoors, the TWS sampler was placed in a room of frequent family activity (typically, the den or family room). Outdoors, the TWS sampler was placed on a porch or patio in close proximity to the home. Samplers were operated simultaneously inside and outside of any given study home during the pilot effort. Additionally, replicate sampling was performed for either inorganic or organic acids at each home through the use of the third TWS sampling leg.

5.2.5.1 TWS Housing Factors

The housing characteristics for the twelve TWS study homes are summarized in Table 5-16. A range of housing age (three homes built in the 1950's, one built in the 1960's, three built in the 1970's, and five built in the 1980's), size (calculated home volumes from 211 m³ to 568 m³), and air conditioning types (five central, two swamp, and five without air conditioning) are reflected in the TWS pilot house study stock. As in the overall residential sampling housing stock, virtually all of the homes were single family residences with detached garages, although one mobile home was sampled. Almost all of the homes (nine of twelve) reported household pets (a potential source of dust and dander). Most were fairly clean, and only one contained a heavy smoker (reported smoking greater than one pack of cigarettes per day).

The TWS data summary appears in Figures 5.2-62 through 5.2-74 and Tables 5-17 through 5-19. As previously described (see Section 2.4.5), the two-week sampler provided samples for determination of fine particle mass and chemistry. The following sections present data discussions summarized in the same manner as the TWS has been previously presented - as vapor phase acids (nitric and hydrochloric), fine particle mass and chemistry, and organic acids (formic

and acetic).

Hydrochloric acid and nitric acid concentrations were obtained from carbonate-coated glass denuders. Gravimetric mass and sulfate concentrations were measured from samples collected on teflon filters. Nitrate and ammonium ion concentration data were corrected for volatilized nitrate by the amount of nitrate collected on the back-up filter. For organic acids, the tabulated data (Table 5-18) reports concentrations from both the front and back-up filters, as well as the sum of both filters. Data flags were noted for two houses at which electrical power problems were reported by the residents during the two weeks of sampling. For these sites, the reported concentrations were calculated using the elapsed time meter readings available from the two-week sampler, but indoor/outdoor ratios may be suspect due to the inability to objectively determine that the paired indoor and outdoor samplers were sampling concurrently. At one home (House #059), indoor teflon filter results were reported to be at levels typically associated with study blank values.

5.2.5.2 Nitric and Hydrochloric Acid Results

Nitric acid (HNO₃) concentrations in the twelve homes sampled showed some variation, with homes ranging in observed HNO₃ levels from 0.5-6 μ g/m³ (see Figure 5.2-62). Indoor concentrations were always lower than the outdoor measurements made in and around the same home, and indoor levels were typically less than half of the observed outdoor concentrations.

Outside HNO₃ samples varied in observed levels from 1-13 μ g/m³, with one home (#007) recording replicated outdoor values of 12.8 and 13.6 μ g/m³. Outdoor samples collected at another home in the same community over the same two-week sampling period varied by a few μ g/m³, but the observed differences represented percentage variations of 16-60%. Replicate samples (Figure 5.2-63) showed much better and consistent agreement for replicate sampling conducted both indoors and outside TWS study homes (compared to samples collected at different homes in the same community at the same time).

Hydrochloric acid (HCl) levels in and around the homes varied from undetectable levels to $3 \ \mu g/m^3$ (Figure 5.2-64), with no apparent explanation for the range of observed concentrations. The ratio between indoor and outdoor HCl levels was erratic, with some home measurements reporting higher indoor levels than outdoors, and other observations reversed. The highest observed sample (outside Home #009) had virtually undetectable levels indoors. Replicate sampling results (Figure 5.2-65) also showed substantial variability. This result was most likely a reflection of the fact that observed levels were quite low, and that the standard deviation of very low measurements was considerable. (This observation was similar to the results obtained in the course of community monitoring using the TWS, as reported in the Phase II report describing the Children's Health Study - see Peters 1995).

5.2.5.3 Fine Particle Mass and Chemistry

A summary of the fine particle ($PM_{2.5}$) mass and chemistry data for the twelve TWS study homes appears as Figures 5.2-66 to 5.2-73. Observed $PM_{2.5}$ mass data (Figure 5.2-66) varied from a few µg/m³ to over 30 µg/m³ indoors and over a slightly smaller range outdoors. Replicate sampling (Figure 5.2-67) showed good agreement between samples whether replicates were collected indoors or outdoors. The largest disparity between indoor and outdoor $PM_{2.5}$ samples was observed in Home #043, where two-week-averaged indoor levels exceeded 32 µg/m³, while simultaneous outdoor levels averaged 6.5 µg/m³. The most likely explanation for this difference was the presence of a regular smoker in the home. This speculation was substantiated by reports of significant smoking behavior in the baseline and follow-up questionnaires that documented the characteristics of this home.

Fine particle sulfate (SO₄⁼), nitrate (NO₃⁻), and ammonium (NH₄⁺) results were consistent and in good agreement, with the possible exception of reported values below 1 μ g/m³. In general, sulfate, nitrate, and ammonium levels reflected seasonal trends, with higher levels observed in and around homes sampled in August and September and values declining in those homes sampled in October and November. (The limited number of overall samples, and the pilot sampling design approach of deployment in one community at a time, made assessment of the relative importance of the community being sampled difficult to examine or unravel from the more substantive seasonal effect). Sulfate levels ranged from 0-3 μ g/m³ indoors and 1-4 μ g/m³ outdoors, and were quite similar indoors and outdoors (see Figure 5.2-68). Replicate sample agreement for SO₄⁼ was excellent (Figure 5.2-69).

Observed NO_3^- levels varied from about 1 to 12 ug/m³, with about half of the homes reporting higher indoor levels than concurrent measurements made outside the home (Figure 5.2-70). Replicate sample agreement (Figure 5.2-71) was generally good, although at very low concentrations (less than 1 ug/m³), such as at Home #083, replicate measurements made both inside and outside differed by a factor of two or more.

Particle ammonium levels (Figure 5.2-72) varied from less than 0.5 ug/m³ to almost 5 ug/m³, with outdoor levels typically equal to or exceeding indoor levels. Replicate sampling (Figure 5.2-73) showed good agreement across the limited sampling concentration range observed.

5.2.5.4 Organic Acids

The observed data for formic and acetic acids is presented in Figure 5.2-74, which plots the indoor/outdoor levels of the measured organic acids and the replicate samples. Indoor concentrations of formic and acetic acids were 2-10 times higher than their respective outdoor levels. Outdoor levels were generally consistent between the two homes measured in the same community, reflecting a regional concentration not driven by local sources. A seasonal trend, with elevated levels of organic acids in August/September declining into the fall, was suggested by the collected data. However, the low number of samples and the lack of any systematic sampling in a given community across seasons make seasonal trend conclusions extremely speculative.

Indoor levels of organic acids varied considerably from home to home, indicative of differing sources (and source strengths) within the home environment. The highest observed indoor acetic acid measurement (69.9 μ g/m³, with a replicate measurement of 72.7 μ g/m³) was collected in a mobile home in Riverside/Mira Loma (Home #009), but values close to this were also observed in more conventional single family residences (67.6 μ g/m³ in Home #001 in San Dimas, and 60.8

 $\mu g/m^3$ in Home #083 in Lancaster).

The highest observation of indoor formic acid was in Home #001 in San Dimas, where 52.9 μ g/m³ (with a replicate sample measurement of 61.4 μ g/m³) was collected. This was significantly higher than any other home (with the next highest home - in Lake Gregory - measured at 32.6 μ g/m³). Survey data or technician interview could not readily provide an explanation for this elevated observation.

5.2.5.5 Assessment of TWS Pilot Deployment

The limited evaluation of the TWS for residential documentation of acids (nitric, hydrochloric, formic, and acetic) and fine particles ($PM_{2.5}$ total mass and sulfate, nitrate, and ammonium ion component contributions to total mass) was informative and successful. Indoor and outdoor levels of sulfate, nitrate, and ammonium ion were generally comparable. Indoor nitric acid was lower than levels found outdoors, for the 12 homes studied. $PM_{2.5}$ mass indoors was often higher than that found outdoors, and when $PM_{2.5}$ levels indoors were found to be several times higher than the concurrent measurement made outdoors, the most reasonable explanation (confirmed by survey) was smoking in the home during sampling. Hydrochloric acids levels were generally low, so indoor/outdoor ratios could not be reliably computed (due to lack of precision at low values).

Elevated acetic and formic acids were found in all homes studied, and may be worthy of further investigation. Indoor/outdoor ratios ranged from 2 to 16 for acetic acid and 2 to 8 for formic acid. Indoor concentrations of acetic and formic acid averaged 5 and 7 times higher, respectively, than concurrent outdoor levels.

Performance of the TWS was generally quite good. In assessing the coefficients of variation for the respective species analyses, the observed pooled standard deviations were generally less than 15% (see Table 5-19), with the exception of hydrochloric acid (which was 57%, due to the low values present, as previously discussed).

The TWS provided a means of obtaining time-weighted data on in-home and near-home acid and fine particle exposures in a reproducible manner, as demonstrated by replicate sample agreement. The body of data, collected in twelve different homes, suggest that the use of the TWS in residential sampling is feasible.

Potential limitations of the method relate to practical field logistics, and acknowledgement of known sampling artifacts. Perceived or actual installation considerations, including size and physical appearance, may somewhat hamper unrestricted deployment of the TWS units. The physical size of the instrument, in its current configuration, may somewhat limit accessibility to homes. As currently configured, a commercial van or other transport vehicle with significant open-space/carry-load capacity is required to deploy single or paired (such as indoor and outdoor) TWS units.

Previous comparative validation of the outdoor version of the TWS with other sampling methods has shown it to have a systematic positive bias of 15-30% for nitric acid, possibly due to nitrous acid interference, and an 11% negative bias for fine particles, probably due to electrostatic charging. These considerations seem manageable, so long as they are predictable.

Modification of the third sampling leg of the TWS, to serve as a partial replicate sampler, was an insightful and valuable improvement to the original design. This modification substantially reduced the amount of equipment necessary for field deployment, but still preserved a means of sample verification.