Title

Characterization of Pollutant Concentrations and Ventilation Rates in New California Residences

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Statement of Work and Preliminary Study Plan for Characterization of Indoor Air Quality, Ventilation and Ventilation-Related Occupant Behaviors in New California Single-Family Houses

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Characterization of Indoor Air Quality, Ventilation and Ventilation-Related Occupant Behaviors in New California Single-Family Houses

Statement of Work

Project Goals: The broad goals of this project are: 1) to determine if ventilation and indoor air quality, in a population of new, production-built, single-family, detached houses built to 2001 Title 24 Building Energy Efficiency Standards, are acceptable based on available guidelines; and 2) to describe the influence of selected key factors, including occupant behaviors, on ventilation rates and indoor air quality in these houses. Achieving these goals within a short timeline is necessary to meet the California Energy Commission's (CEC) summer 2005 deadline for the project to significantly inform the Title 24 Standards revision process.

Project Objectives: The objectives of the project are to answer a series of questions related to ventilation rates and indoor air quality (IAQ) in production-built, new, single-family, detached (SFD) CA homes permitted to 2001 Title 24 standards:

<u>Ventilation questions</u>
- What is the range and distribution of measured whole-house ventilation rates?
- What proportion of the ventilation rates meet ASHRAE 62-1999 requirements?
- How do certain house characteristics influence ventilation rate?

<u>Occupant behavior questions</u>
- How frequently do occupants use windows and doors to provide ventilation, and what is the relationship of outdoor temperature to these behaviors?
- How frequently do occupants use exhaust fans in bathrooms and kitchens?
- How do these occupant behaviors influence ventilation rates?

<u>Indoor air quality questions</u>
- In what proportion of houses is IAQ acceptable based on available agency guidelines related to airborne contaminant concentrations?
- How do ventilation rate, occupant behaviors, and selected house characteristics influence indoor concentrations of target airborne pollutants?

Project Tasks: The study will be accomplished through a series of defined project tasks. A large number of tasks must be completed before the field survey can be initiated. Since most tasks are interrelated and the time frame for the study is compressed, many tasks will be conducted in parallel. The tasks are enumerated here in outline form. The subsequent section presents a narrative description of a study plan designed within this framework to address the project goals and objectives.

A. Establish schedule for completion of key project tasks and milestones

B. Select study sample of houses from the defined, targeted study population
   1. Define study population to include several population centers in distinct CA climate zones with a range of heating/cooling climate conditions
   2. Define sampling frame for the study
   3. Establish eligibility criteria
   4. Identify data sources for targeting potentially eligible units
   5. Determine key criteria for determining study size and desired precision limits
   6. Determine minimum sample size of houses based on available data on key parameters
   7. Adjust study design as needed to allow sufficient sample size for key analysis objectives within available resources
   8. Develop statistical design to select eligible units

C. Develop questionnaire to determine ventilation-related occupant behaviors over study interval and over longer periods
   1. Using validated questionnaires where possible, select questions to obtain demographic data and assess occupants' use of window and door opening to provide ventilation
   2. Select questions to assess occupants' use of kitchen/bathroom fans and other ventilation equipment

D. Develop survey instrument to characterize houses and potential indoor/outdoor pollutant sources
   1. Using validated survey instruments where possible, select questions to physically characterize the site and the house including mechanical equipment and energy sources
   2. Select questions to characterize potential indoor and outdoor sources of pollutants being studied

E. Obtain required human subjects approval
   1. Prepare documentation to obtain human subjects approval from authorizing organization(s)
   2. Submit and obtain human subjects approval

F. Select physical and chemical parameters and appropriate monitoring/measurement methods
   1. Establish set of physical and chemical parameters to be used to assess adequacy of ventilation and IAQ
   2. Provide justification for selection of pollutants based on likelihood of presence in new homes, association with or influence by ventilation, and potentially significant health concerns

3. Select cost-effective monitoring/measurement methods to provide environmental, ventilation and pollutant concentration data over at least a one-week interval

G. Develop field and laboratory protocols for physical and chemical measurements
   1. Using existing methods and protocols where possible, develop specifications and detailed field operation protocols for measurement of environmental parameters, ventilation rates and pollutant concentrations
   2. Using existing methods and protocols where possible, develop detailed analytical protocols for laboratory measurements

H. Develop data handling and processing system
   1. Select database and other software for handling and processing data
   2. Develop and document database system to maintain data from questionnaires, surveys, field measurements and laboratory analytical reports
   3. Develop control system to track surveys, samples and analysis reports
   4. Develop system to resolve missing, incomplete or unintelligible data entries

I. Develop quality control and assurance procedures for field and laboratory measurements and data handling
   1. Designate a quality control manager for the study
   2. Develop quality control plan for field measurements including maintenance, calibration, operation and data downloading from continuously operating instruments
   3. Develop quality control plan for collection of field samples that includes sample labeling, logging, handling, shipping, collection of blanks, and deployment of control and duplicate samples
   4. Assess adequacy of laboratory quality control procedures to assure reliability and accuracy of data including type and frequency of calibrations and use of laboratory blanks, control samples and replicate analyses
   5. Implement chain-of-custody procedures for samples and data forms
   6. Develop manual and/or automated survey data entry procedures to ensure accuracy and completeness

J. Select and train field staff
   1. Designate a field staff scientific leader for the study
   2. If any field labor is to be subcontracted, obtain and review qualifications of potential subcontractors
   3. If required, select subcontractor(s) and execute contract(s)
   4. Train field personnel in field procedures including: interactions with occupants; implementation of questionnaires and surveys; maintenance, calibration and operation of field instruments; sampler placement, deployment and collection; data recording and downloading; and safety

K. Conduct practice/pilot studies
   1. Have field staff practice questionnaires, checklists, on-site measurements, sample collection and data recording in actual houses
   2. Develop and test a complete data information shell

3. Process these collected data into database to ensure accuracy

L. Recruit participants
   1. Select pool of potentially eligible homes
   2. Obtain contact information (e.g., addresses, phone numbers) for occupants
   3. Set up 1-800 response line and e-mail access for response to questions from occupants
   4. Establish incentives for participation
   5. Prepare introductory letters and other recruitment materials
   6. Contact occupants by mail and phone to establish eligibility and interest
   7. Establish appointments followed up with telephone reminders
   8. Prepare letters to thank participating occupants

M. Perform field study in adherence with project procedures and schedule

N. Establish relevant agency guidelines for comparison with measured parameters
   1. Refer to ASHRAE Standard 62-1999 for minimum ventilation rate requirements and guidance on IAQ for human occupancy
   2. Refer to Cal-EPA and CA Dept. of Health Services programs and documents for guidance on acceptable indoor and outdoor air quality levels to protect human health
   3. Emphasize safety issues and chronic exposures to toxic pollutants with the potential to produce serious health outcomes

O. Process data and produce summary statistics
   1. Validate data entered into database for accuracy
   2. For continuous data, determine ranges and averages over appropriate time intervals
   3. For measurement data, convert raw data into ventilation rates and concentrations appropriately accounting for limits of detection, blank values and duplicate samples and analyses
   4. Determine response and completion rates for questionnaire and survey data
   5. Generate summary statistics for measurements such as percent above limits of detection, fraction of levels above specified guidelines, means, geometric means if lognormal, percentile distributions
   6. Determine precision of measurement estimates including standard errors and confidence intervals (analytic and overall)

P. Conduct data analysis to answer project objectives
   1. For key parameters of interest such as ventilation rate, occupants' use of windows and doors for ventilation, occupants' use of bathroom and range fans, and house characteristics, describe range and distributions among houses overall; and, as feasible, among houses by subgroups, e.g., different climate zone and different seasons
   2. Describe relationships between ventilation rates and selected housing characteristics
   3. Describe proportion of ventilation rates meeting ASHRAE 62-1999 requirements, among houses overall and, as feasible, by subgroups
   4. Describe frequency of occupants' use of windows and doors for ventilation, and the relationship of outdoor temperature to these behaviors
   5. Describe frequency of occupants' use of exhaust fans in bathrooms and kitchens

6. Describe relationships between these occupant behaviors and ventilation rates
7. For each specific airborne contaminant on which agency guidelines are available, calculate proportion of houses in which IAQ is acceptable
8. Describe how ventilation rate, occupant behaviors, and selected house characteristics influence indoor concentrations of key airborne pollutants

Reporting Requirements: The tasks and the time schedule for completing key milestones establish the interim reporting requirements listed below. The draft final report must be submitted in time to allow review and comment by CEC and submittal of the final report by July 30, 2005.

<u>Interim reports</u>

- January 30, 2004: Report presenting completed questionnaires, recruitment materials and selection of study population to city level
- March 31, 2004: Report presenting quality assurance/quality control plan and field operation, laboratory analysis and data handling protocols
- June 30, 2004: Report presenting progress on pilot study and first several months of field data collection and measurements
- December 31, 2004: Report presenting progress on next six months of fieldwork
- March 31, 2005: Report presenting progress on completion of field work and first stage of data analysis to produce summary statistics

<u>Final report</u>

- May 31, 2005: Submit draft final project report.
- July 31, 2005: Submit final project report. This schedule assumes CEC comments would be received within 30 days of submittal of draft report and that requested revisions could be completed within 30 days of receiving comments.

Characterization of Indoor Air Quality, Ventilation and Ventilation-Related Occupant Behaviors in New California Single-Family Houses

Preliminary Study Plan

Introduction

We have developed a preliminary study plan that is intended to address questions of specific interest to the CEC related to the Title 24 Building Energy Efficiency Standards for new residences. As the time and resources available for the study are limited, the information and measurements to be obtained are focused on these questions. Consequently, the plan may not fully address related issues that are of importance to the California Air Resources Board and the Department of Health Services. The Statement of Work presented our understanding of the CEC's goals and objectives regarding the study of ventilation rates, ventilation-related occupant behaviors and indoor concentrations of targeted air pollutants in new, single-family, California houses. Our proposed approaches to this study are described below in narrative form following the topics outlined in the Statement of Work.

A. <u>Establish schedule for completion of tasks and milestones</u>

We have proposed a tentative schedule for completion of the major project tasks outlined in the Statement of Work and discussed in detail below (Table 1). Due to the very limited time available for completion of the study, it is imperative that a contract be established before January 2004. There are numerous tasks to be completed prior to initiation of fieldwork in April 2004 including obtaining human subjects approval. Since the human subjects review process requires submission of numerous completed documents (discussed in Section E), some mechanism to allow work on these documents and on other key preliminary tasks in the last quarter of 2003 is recommended.

B. <u>Select study population of houses</u>

We would elect to focus the study on typical, new, detached houses designed and permitted to the most current version of Title 24 Building Energy Efficiency Standards (2001). Since the study must be completed on an abbreviated time schedule, the number of housing units that can be included is necessarily restricted. Thus, we would attempt to minimize the number of variables, which could potentially affect the outcomes and the consequential need for more units, by focusing the study on a single housing type with several additional restrictions. The selected type, single-family detached (SFD) houses, represents the majority of the new housing units being constructed in California. For example in 2002, 77 percent of the new housing units permitted in CA, excluding public housing and manufactured houses, were SFD houses (U.S. Census Bureau, 2003). Only on-site, production-built houses within subdivisions would be considered, as these comprise the majority of the new SFD houses. Townhouses, condominiums, and apartments with shared walls would be excluded because they may have different ventilation characteristics than detached structures. We would only consider owner-occupied houses under the assumption that owners are more likely than renters to be familiar with the mechanical and other energy-related features of their houses. We would only include houses that were at least three months old at the time of the measurements since indoor air concentrations of gaseous pollutants resulting from material emissions may be elevated in the first several months after completion and, thus, not be representative of potential long-term exposure. Our past and current research indicates that, subsequent to a short initial period, the emissions of key pollutants such as formaldehyde are relatively constant over periods of months (e.g., Hodgson et al., 2000). Houses in which smoking occurs indoors (i.e., houses without a strict non-smoking policy) would be excluded, as smoking is an additional major source of some of the pollutants of interest such as particles (Wallace et al., 2003). Thus, inclusion of smoking would necessitate sampling more houses to estimate the effect of this variable on pollutant concentrations. Finally, we would exclude houses that are on average, upwind and very near (within 100 m) or primarily downwind and near (within 350 m) major roadways, such as freeways. Residences within this zone are likely to have concentrations of traffic-related contaminants (e.g., nitrogen oxides and particles) that are elevated over regional background levels (Singer et al., 2002 and 2003; Zhu et al., 2002a-b). We would utilize, to the extent possible, ambient concentrations measured at government monitoring sites as the measures of outdoor concentrations. Inclusion of houses within the zone of freeway influence would necessitate conducting outdoor measurements at each house, would increase the monitoring costs.

Climate and season are two essential variables to include in the study because they influence house infiltration rates and likely occupant ventilation-related behaviors are climate and season.

The CEC has divided CA into 16 geographical areas with internally homogeneous climatic conditions based on energy use, temperature, weather and other factors. At a minimum, houses in two (or possibly three) of these climate zones should be studied. Field work in the houses would be spread over about ten months (approximately April 2004 through mid-February 2005), allowing the study to incorporate periods of peak cooling and heating as well as transitional periods in the spring and fall.

A graphic description of how we currently plan to select a study sample of eligible SFD houses designed to the 2001 Title 24 standard from the defined, targeted study population is presented in Figures 1-2. The multi-stage cluster design shown in Figure 1 identifies and defines the study population in preparation for sample selection and recruitment of study houses and gives hypothetical examples of possible choices. There are three stages, or clusters, specified, with the last also serving as the first random sampling stage. The three stages are:

1. In Southern CA, target one climate zone (CZ) and in Northern CA, target one or two CZs. The selection of CZ(s) in Northern CA would be influenced by logistical considerations (i.e., proximity to the research team's base of operations);
2. In each CZ, target one (or possibly two) county with records of recent SFD housing construction; and,
3. In each county, randomize the list of cities and unincorporated areas, which have new SFD housing developments based on city/county planning office and real estate records. From the top of the list select two cities or unincorporated areas. We anticipate that U.S. Census data available annually (U.S. Census Bureau, 2003) can be used to determine how representative the selected sample is of the study population, by CZ and county.

For each selected city, we would obtain a list of housing developments (HDs) meeting a defined size criterion selected to optimize the chance of obtaining production-built houses. From a randomized list of HDs, we would select two or three starting from the top. All addresses within the selected HDs would be obtained and randomized. From the top of the list, we would select houses for recruitment with the goal of securing five houses per HD. Figure 2 diagrams the entire selection process and also summarizes the selection or inclusion criteria for the cities and HDs as well as the eligibility criteria for individual houses (discussed above). Our current ideas for implementing the recruitment procedures are discussed below in Section M.

The estimation of the minimum sample sizes needed to answer key questions with sufficient precision is beyond the scope of this document, but should be performed before the study plan is finalized. This can be accomplished in part by utilizing procedures borrowed from studies that assessed differences in health outcomes, in combination with the results of previous residential field studies that measured ventilation rates and pollutant concentrations in CA and other states (e.g., Callahan et al., 1995; Whitmore et al., 1999; Naumova et al., 2002 and 2003; Weisel et al., 2002). The first steps are to identify the key criteria for determining sample size and to establish the desired precision level. For example, a particular sample size would be needed to estimate key parameters such as ventilation rate or indoor formaldehyde concentration in the overall study sample or in subsets by climate zone or season within defined precision limits. Another size may be needed to estimate relationships, within defined precision limits, between variables such as between ventilation rate and indoor concentrations of a specific pollutant. Using an adaptive sampling process might be an efficient way to identify such relationships. Practical considerations dictate that the optimal study design must be adapted to allow sufficient sample size for key analysis objectives within the time and resources available for the study.

At this stage in the design process, we have focused on the available time and the limited resources to conduct the proposed study to answer key questions posed by the CEC, and have estimated what we think may be an appropriate, reasonable sample size of approximately 80-120 houses. We believe this design will allow us to address the major questions while completing the recruitment, field visits and data analysis with the allotted time schedule.

C. <u>Develop questionnaire to determine ventilation-related occupant behaviors</u>

We would assemble and develop, as necessary, questionnaires to collect basic occupant demographic data, historical data, key house attributes and ventilation-related occupant behaviors. The field technicians would administer questionnaires as in-person, survey interviews with an adult participant in the house. The questionnaires would ask occupants about when they moved in, the age of the house, the numbers of rooms, doors and windows, the types of HVAC and mechanical ventilation systems, etc. We would ask the occupants about their use of windows and doors for ventilation, exhaust fans in bathrooms and kitchen, HVAC systems, whole-house fans and other mechanical ventilation systems over both the week-long study interval (the study period activity questionnaire) and in general across seasons in which the participant has lived in the house (the baseline questionnaire). Each of these questionnaires, in final form, would take about 15 minutes to complete. We would utilize to the extent possible, topics and actual questions developed and validated in previous U.S. studies (e.g., Freeman et al., 1999; Devine, 1999; Weisel et al., 2002). The Washington State University survey of ventilation-related behavior in new WA State houses (Devine, 1999) is particularly relevant to these questionnaires because it included questions on window-opening behavior over seasons. Table 2 lists topics and questions regarding occupant behaviors drawn from the referenced studies that we would consider using in the baseline and study period activity questionnaires.

D. Develop survey instrument to characterize houses and potential pollutant sources

In the residential setting, our experience is that participants do not want technicians to walk through their houses to obtain survey information. A questionnaire that collects the same information through specific multiple choice responses is a more acceptable instrument. Thus, the baseline and study period activity questionnaires also would be designed to obtain relevant information regarding the potential sources of the targeted air pollutants and their use by occupants. For example, we would ask occupants about their use of water (a potential source of chlorinated volatile organic compounds (VOCs)); cooking appliances, fireplaces and candles (potential sources of particles and combustion byproducts); attached garages (potential sources of particles, carbon monoxide and VOCs); and consumer products (potential sources of VOCs). In addition, we would attempt to devise questions to obtain information regarding the presence and quantities of the major sources of formaldehyde in new houses (i.e, cabinetry and countertops, interior doors, and composite wood subfloors) as identified in a detailed study of a new manufactured house (Hodgson et al., 2002). This portion of the survey instruments, in final form, would comprise approximately 33-50% of the questions. Table 3 lists topics and questions regarding air pollutant sources and pollutant-related behaviors drawn from the studies referenced above that we would consider incorporating into the baseline and study period activity questionnaires.

In addition, there would be some technician observations recorded, including simple measurements of the ceiling and wall heights and floor areas of rooms in a house to calculate an estimated house volume needed for the determination of ventilation rate.

E. Obtain human subjects approval

We would prepare the required forms and the documentation to obtain human subjects approval from the LBNL Human Subjects Quality Assurance Committee and then from the U.C. Berkeley Committee on the Protection of Human Subjects (a sequential process). We likely would be required to have a full review due to the proposed combination of interview surveys and environmental and indoor air quality measurements in private residences. We do not anticipate a problem in obtaining approval, based on past experiences receiving full protocol approval or waiver approvals. However, this process to submit paperwork and obtain final human subjects approval typically takes up to three months. The required forms will include the developed participant consent forms (one copy to remain with research team, one copy to remain with participant), written recruitment materials (e.g., introductory letter and study brochure), outlined field team standard operating procedures and the final questionnaires, including citations documenting the origins of questions. It must be emphasized that no fieldwork can begin until approvals are official, and approvals cannot be requested until funding is received and the required documentation is prepared. The latter involves further planning of field sampling and recruitment procedures.

F. Select physical and chemical parameters and monitoring/measurement methods

Our design for the proposed study is based on a sampling duration of approximately one-week, which would include weekend days. This interval was selected so that the measured parameters would be representative of a weekly cycle of residential occupancy and activities. We would plan to make two visits to each house, once at the beginning of the period to administer questionnaires and initiate monitoring/measurement and once at the end to terminate monitoring/measurement. This design strongly influenced the choice of methods for the study.

The physical and chemical parameters targeted for monitoring or measurements in the proposed study are listed in Table 4, along with the selected methods. The key physical parameter for this study is ventilation (i.e., air exchange) rate. Whole-house ventilation rates would be determined using a non-toxic tracer gas method employing passive perfluorocarbon tracer (PFT) gas sources and samplers. The single PFT gas would be perfluoromethyl cyclohexane (PFMCH). With this method, diffusion sources of the PFT are placed at several locations in a house, and the PFTs are sampled by passive diffusion using capillary absorption collection tubes (CATs) in the main living area. The PFT sources and CATs would be deployed over a one-week interval. Sources would be preconditioned at a typical indoor temperature to reduce the time needed for their temperature and emission rates to equilibrate to the conditions of the study houses. The magnitude of the potential error induced by difference in preconditioning and placement temperatures would be estimated. The PFT technique has been used in previous residential studies in CA, which found log-normal distributions of measured ventilation rate (Wilson et al., 1986, 1996; Pandian et al., 1993 and 1998; Murray and Burmaster, 1995; Weisel et al., 2002). PFT and CAT attributes, including physical descriptions, materials, safety, background environmental concentrations, source and sampler placement, storage and handling procedures, source emission rates, sampling rates, accuracy and analytic precision have been described in a number of publications (Dietz and Cote, 1982; Leaderer et al, 1985; D'Ottavio et al, 1988; Sherman, 1990; Wilson et al, 1996; Weker, 1999; Shendell, 2003; Shendell et al., 2003a). PFT sources and CATs are available for rental from several suppliers, which also provide analytical services.

Indoor air temperature is required to determine PFT source diffusion rates. Indoor moisture as indicated by relative humidity (RH) is a measure of how well water vapor sources are handled by bathroom and kitchen fans and by ventilation. Indoor and outdoor temperatures are a likely determinant of occupant behaviors affecting ventilation. Indoor temperature and RH would be measured at one height in a central living area of a house. Outdoor temperature and RH also would be measured at one location and height. These measurements would be obtained using HOBO H8 family sensors with data loggers (Onset Corp, Bourne, MA), which can obtain and store measurements approximately every several minutes over a one-week sampling interval.

If resources were adequate, we would measure infiltration rates and duct leakage rates in a small subset of the houses. This would be accomplished using the DeltaQ methodology developed by LBNL (Walker et al., 2001; Walker and Sherman, 2002). The DeltaQ method combines envelope and duct leakage by performing blower door tests with the house operating in two modes, i.e., with the air handling unit off and on.

Our selections of the gaseous and particulate pollutants to be measured were based on several criteria: 1) they are known to be present in houses due to significant indoor and outdoor sources;

2) their concentrations are likely to be strongly influenced by house ventilation rate; 3) they have the potential to cause health effects at relatively low concentrations as the result of indoor and outdoor exposures; and 4) these potential health effects are generally chronic in nature (i.e., noncancer or cancer effects due to relatively long-term exposures). The target chemical pollutants we selected are carbon monoxide (CO), nitrogen dioxide (NO_2) (and possibly total NO_X), ozone (O_3), benzene, toluene, xylene isomers (i.e., BTEX), chloroform, and formaldehyde. Respirable particulate matter ($PM_{2.5}$) was also targeted. No pesticides, polycyclic aromatic hydrocarbons or other semi-volatile chemical pollutants would be assessed due to the likely need for additional method development or validation, relatively high labor and equipment costs for sample collection, and high analytical costs.

A number of the selected pollutants are derived from vehicle exhaust and other combustion sources. Exposure to traffic and combustion related pollutants, both gases and particles, has been associated with a variety of health outcomes, particularly in children, including respiratory symptoms and decrements in lung function. Low level CO exposures may affect unborn babies, infants, and people with anemia or a history of heart disease. Compared to healthy people, children, and individuals with respiratory illnesses such as asthma, may be more susceptible to the effects of nitrogen oxides. In nonsmoking houses, the presence of automobiles in attached garages and unvented combustion appliances may be an indoor source of CO, NO_X species and respirable particles. Ozone is predominantly generated outdoors. When O_3 enters buildings, it reacts with interior surfaces and its concentrations decrease relative to outdoors. Since the decay in indoor O_3 concentrations is rate limited, increasing the supply rate of outdoor air through increased ventilation results in a higher indoor/outdoor O_3 ratio.

Benzene, toluene and xylene isomers (BTEX) are components of evaporative fuel emissions and motor vehicle exhaust and, thus, also may be related to the presence of motor vehicles in attached garages. Toluene and xylenes may be emitted by some materials and products used to finish interiors of new houses such as adhesives (Hodgson, 1999) and solvent-based paints. They may also be present in some consumer products such as nail care products (Wallace et al., 1991). Chloroform is present in many domestic water sources as a disinfection byproduct. Chloroform enters indoor air during tap water usage. Models for simulating the transfer of contaminants, such as chloroform, from tap water to indoor air and for predicting indoor inhalation exposures have been developed. (McKone, 1987; Wilkes et al., 1996). Formaldehyde is probably the most prevalent compound of concern with respect to both acute and chronic toxicity that is likely to be present at elevated levels in new houses due to emissions from composite wood products and other materials (Hodgson et al., 2000 and 2002). Benzene is a known human carcinogen, and chloroform and formaldehyde are probable human carcinogens. These three compounds have low cancer unit risk factors for lifetime exposures (U.S. EPA, 2003).

The sampling methods for the chemical and particulate pollutants generally were selected because they are relatively easy to implement in a large-scale field study and they can produce long-term, integrated average concentrations over the desired weeklong sampling interval. The use of methods for the chemical pollutants requiring active sampling with pumps was avoided because of the additional time and labor involved in making these measurements and their restricted ability to make integrated measurements over more than 12- or 24-h periods.

The target volatile organic compounds (VOCs) (i.e., BTEX and chloroform) would be collected with passive 3M OVM 3500 badges. These samplers have been validated in laboratory studies (Chung et al., 1999a-b) and have been used in studies of U.S. residences and office buildings (e.g., Shields et al., 1996; Morandi and Stock, 1998; Weisel, 2002) and in European building studies (e.g., Schneider et al., 1999). These studies and others in schools (e.g., Shendell et al., 2003b), collectively, validated this passive sampler for measuring a wide range of indoor and outdoor VOC concentrations under a range of typical meteorological conditions for 24-48 hour or longer (e.g., one-week or longer) integrated periods. Schneider et al. (1999) found no significant difference in measured median indoor air concentrations with sampling height across three heights, which suggests any safe location greater than 1 meter from walls and obvious sources would be appropriate in the study houses.

The passive sampler chosen for HCHO has been validated from 5 ppb to 5 ppm, which is sufficient for one-week integrated averages in new homes (Levin et al., 1988; Levin and Lindahl, 1994). The passive Ogawa sampling system for O_3, NO_2, and total NO_X has been field tested and validated by several studies. These include microenvironment O_3 (indoor home, outdoor home, indoor school) in Mexico City (Romieu et al., 1998); outdoor O_3 by the U.S. National Parks Service (Flores et al., 1998); and NO_2 and total NO_X outdoors and inside school buildings in the East Bay of CA (Singer et al., 2002 and 2003). The CO passive dosimeter has been validated in laboratory and field settings (Apte et al., 1999).

Sampling for particulate matter would require the use of pumps. We have selected small inertial impactors or personal exposure monitors (PEMs) operated with small programmable pumps (AirChek 2000, SKC, Inc.). Particulate matter less than 2.5 micrometers in aerodynamic diameter ($PM_{2.5}$) would be collected. This method was used and validated in the Particle Total Exposure Assessment Methodology (PTEAM) study (Thomas et al., 1993). More recently, the method was used to measure PM_{10} and $PM_{2.5}$ over two seasons at ten East Bay, CA schools (Singer et al., 2002). In that study, a simple housing was developed and used inside classrooms to reduce pump noise to nearly inaudible levels.

California operates an extensive state and local air monitoring network, which obtains data on criteria air pollutants, selected toxic air contaminants, and $PM_{2.5}$ mass and speciation throughout the state. Some of the pollutants of interest to this project are measured continuously in ambient air at the monitoring locations. These include ozone, NO_X species and CO. Toxic air contaminants including formaldehyde, BTEX and chloroform are monitored approximately every 12 days at 18 locations. $PM_{2.5}$ is monitored daily or at least once every six days at 82 sites. To reduce monitoring costs, we would access and utilize, to the extent possible, ambient concentrations of the study pollutants measured at the statewide monitoring sites as the measures of outdoor air concentrations.

G. <u>Develop field and laboratory protocols for physical and chemical measurements</u>

The field work schedule and field protocols would be developed from those implemented and proven valid in previous studies conducted by LBNL staff (e.g., EOHSI, 1999; Shendell et al., 2002; Singer et al., 2002 and 2003). As in the previous studies, the field procedures would attempt to minimize the burdens imposed upon participants by not restricting their activities, by keeping the survey questionnaires short, and by being neither invasive nor disruptive. Onsite safety issues such as the placement of samplers and tracer-gas sources in houses with small children and pets would be carefully considered. The goal for this study would be to limit the time for each of the two visits to the study houses to one hour or less.

The required analytical measurements would be subcontracted to commercial laboratories. The primary intent of this decision is to focus LBNL/UCB's efforts on the other study tasks and to take advantage of the standard operating procedures (SOPs) and quality assurance/quality control (QA/QC) procedures developed by laboratories over years of experience. We would require that all analyses be performed using appropriate documented and validated methods (Table 4).

The weighing of particulate matter filters would be conducted at LBNL using well-documented protocols that have been used in our other recent field studies (e.g., Singer et al., 2002).

H. Develop data handling and processing system

We would develop a data handling and processing system to accommodate the large amount of qualitative data (responses to baseline and study period activity questionnaires, field technician observations, etc.) and quantitative data (indoor and outdoor air temperature and RH, pollutant parameters including analyte masses, sampler deployment times, sample volumes, etc.). This system would be based on Microsoft (MS) Access database software. Forms would be created in MS Excel (transferable to MS Access) to serve as a control system to track the questionnaire surveys to and from the field, and the samples to and from both the field sites and subcontracted laboratories.

We would develop an internal quality control system, similar to other previous LBNL and UCLA studies (e.g., Shendell et al., 2002; Shendell, 2003; Singer et al., 2002), to enter survey data into the database. This protocol would include the definition of acceptable response fields in MS Access, validation of entries with re-entry of a randomly selected number of surveys by a different field technician, and a procedure to resolve missing or incomplete survey responses.

The quantitative data for entry into the database would come from multiple sources and would be in a variety of forms. The sources include:

1) Field measurements (indoor and outdoor air temperature and RH data files, particulate matter pump calibration and run-time data, sampler deployment and collection times);

2) Laboratory analytical reports (masses of target pollutants in field, blank, and control samples);
3) Ventilation rates (calculated from raw data in a separate MS Excel database that previously has been validated (Weker, 1999; Shendell, 2003; Shendell et al., 2003a).
4) Weather and pollutant monitoring data available from the nearest governmental weather and air monitoring central site stations (wind speed and direction, outdoor $PM_{2.5}$, NO_2, CO and O_3 concentrations);

Final data spreadsheets with properly coded/named columns and formatted cells would be prepared for export to SAS Enterprise Guide software (v.1.3-2.0, based on SAS v.8.2-9.0, Cary, NC). SAS would be used for the calculation of descriptive statistics, correlation coefficients, comparisons of means, and other statistical analyses required by the study.

I. <u>Develop quality control and assurance (QA/QC) procedures for field and laboratory measurements and data handling</u>

A member of the LBNL/UCB staff would be designated as the quality control manager for the study. It would be the general responsibility of the quality control manager to ensure that all quality control procedures necessary for the successful completion of the study are developed, implemented and adequately documented and that quality control objectives (e.g., percent completion goals for measurements) are achieved.

Quality control plans would be adopted and/or developed for all aspects of the study as specified in the outline. Our reliance on previously documented and validated procedures for field operations and data management and our use of subcontract laboratories for analyses is intended to reduce the amount of new documentation required. For the laboratories, we would require and confirm by review that analyses are performed using the correct methods, SOPs are current and thorough, appropriate QA/QC practices are followed, and documentation is adequate. Chain-of-custody procedures would be implemented to document the movement of questionnaires, other data forms, and samples.

J. Select and train field staff

The field study effort would be under the scientific leadership of a LBNL/UCB staff member. Our study design requires two field teams, one in Southern CA and one in Northern CA. Our first choice for would be to obtain the Southern CA team through a subcontract with the School of Public Health, UCLA. The team would likely consist of master's students under the direction of a doctoral student in the Environmental, Science and Engineering Program who has completed most of the required course work. The Northern CA team would be based at LBNL/UCB and also might consist largely of graduate students. The field teams would need to be recruited and subcontracts completed in January and February 2004 in order to have adequate time for training prior to the March 2004 practice/pilot studies.

K. Conduct practice/pilot studies

The assessment of a limited number of practice or pilot study houses in both Northern and Southern CA regions would be conducted by mid-to-late March 2004 to provide final training for the field staff and to test the database system. Two to three new or newer houses in each region otherwise meeting the eligibility requirements would be recruited, most likely for convenience from among LBNL and University of CA colleagues and staff. Field staff would practice interaction with participants in actual houses, administration of the baseline and study period activity questionnaires, implementation of the on-site measurements including sample deployment and collection, and other data collection and recording tasks. In addition, the field staff would test the data information shell in the field and/or back at their bases of operation and process the collected data into the quantitative and qualitative study databases. Other staff would review the databases for accuracy and perform data analyses to produce summary results for the pilot study houses.

L. Recruit participants

Recruitment would be conducted in strict adherence to a predetermined multi-step process and in compliance with guidelines for human subjects. Multiple, no-cost communication lines for participants would be established. For example, a 1-800 response line and e-mail accounts accessible by the LBNL/UCB (Northern CA) and the Southern CA field teams would be established for the receipt of and timely response to questions from occupants of participant houses before and during the study period.

We would obtain contact information (e.g., addresses, phone numbers) for each house in the randomly selected HDs in the randomly selected cities. This information, based on U.S. Postal Service records, can be purchased from private companies. We would prepare an introductory letter and a recruitment brochure (i.e., a one-page description of the study and its goals as related to California citizens) in both English and Spanish. Overall, within a two-week period and in groups of about 10 houses, we would contact occupants by mail and phone and/or in person, to establish eligibility and interest, according to a defined protocol. For example, up to three phone calls, with each at least two days apart, would be made at various times between 8 am and 9 pm on weekdays, with at least one phone call between 6-9 pm on Monday through Thursday. During the recruitment process, HDs and houses would be excluded under defined circumstances. For example, HDs and houses (i.e., addresses) would be excluded due to lack of cooperation or non-response, respectively; houses would be moved to the end of the randomized list if they were not currently occupied for three months but likely would be occupied for this period later in the study. For each contacted house that is eligible and recruited into the study, we would establish appointments for the initial and final sampling visits; we would follow up with telephone or e-mail reminders, per the preference of the participants.

For participation, we would establish modest financial and/or educationally oriented incentives, based on experiences of previous U.S. residential exposure assessment studies (e.g., Whitmore et al., 1999; Weisel et al., 2002). An optional follow-up task is to prepare letters to thank participating occupants.

M. Perform field study

The main field study would be conducted from April 2004 to mid-February 2005, a period of 10.5 months. This dictates that, field measurements, on average, would need to be completed in approximately 10 houses per month overall. However, a target schedule would be developed to ensure that the measurements are spread throughout the range of climatic conditions. The goal of the schedule would be to obtain sufficient numbers of houses in climatic conditions when windows and doors are likely to be closed.

N. <u>Establish relevant guidelines for comparison with measured parameters</u>

ASHRAE Standard 62-1999 establishes minimum ventilation rate requirements for residences based on house size and the numbers of planned occupants (i.e., "by volume" and "by occupant" requirements). These ASHRAE requirements would serve as the basis for determining what proportion of the measured ventilation rates are acceptable.

Interest in the outdoor environment and cancer risk has dominated governmental regulatory efforts. Even though indoor exposures are widely recognized to be more important than ambient exposures, there is little governmental guidance on acceptable indoor air concentrations of air pollutants. One exception is formaldehyde (Table 5). The CA Air Resources Board in the early 1990s established formaldehyde guidelines that were intended to protect residential occupants (CARB, 1991). The highest acceptable concentration of 100 ppb was designated as a ceiling or action level (i.e., steps should be taken to reduce concentrations to below this level even if occupants are not experiencing symptoms). A concentration of 50 ppb or less was listed as a target level to reduce cancer risk with the provision that concentrations be reduced to the lowest possible practical level because of the lack of an absolutely safe standard. The CA Office of Environmental Health Hazard Assessment (OEHHA) has more recently established acute and chronic (non-cancer) reference exposure levels (RELs) for formaldehyde and a number of other chemicals (OEHHA, 2000 and 2001). The acute REL for formaldehyde of 75 ppb is for a one-hour exposure and is intended to be protective against mild eye irritation. The supporting data were from a study of humans. Chronic RELs are intended to be concentrations at or below which adverse health effects are unlikely to occur in a continuously exposed and diverse general population. The chronic REL for formaldehyde is based on a review and analysis of effects including eye and nasal irritation. The primary basis for the REL were data from workers exposed over a period of years and the derivation of a no adverse effects level of 32 $\mu g\ m^{-3}$ (26 ppb). A ten-fold intraspecies uncertainty factor was applied to arrive at the REL. of 3 $\mu g\ m^{-3}$ (2.4 ppb). Based on this CA guidance, it appears that the target level for the average formaldehyde concentrations in new residences should be approximately 50 ppb, but lower levels are desirable.

For the criteria air pollutants to be monitored in the study, it may be possible to rely on ambient air quality standards for guidance. However, there is no direct correlation between the time scales of the standards and the study's sampling interval. A chart from the CA Air Resources Board that includes the CA and Federal standards for O_3, $PM_{2.5}$, CO and NO_2 is attached as an appendix. In CA, there are one-hour standards for O_3 and NO_2, an 8-h standard for CO and an annual mean requirement for $PM_{2.5}$. A proposed CA 24-hour standard for $PM_{2.5}$ is being reviewed.

Measured concentrations of VOCs with cancer effects would be compared to their respective air concentrations at specific risk levels (i.e., 1×10^{-5} and 1×10^{-6}) obtained from the IRIS database (U.S. EPA, 2003).

O. Process data and produce summary statistics

We would process the data and produce summary statistics as specified in the Statement of Work outline. The summary statistics would be presented for both the overall study and for houses by different climate zone and different seasons.

P. Conduct data analysis to answer project objectives

Again, following the detailed steps specified in the Statement of Work outline, we would analyze the data to the extent possible to answer the questions posed regarding ventilation, ventilation-related occupant behaviors and indoor air quality. Associations between ventilation rates and housing characteristics, between occupant behaviors and ventilation rates, and between indoor concentrations of pollutants and other parameters would be analyzed using multivariate regression models. Since we would have measured ventilation rates and indoor pollutant concentrations and would have obtained regional air pollutant concentrations and basic house parameters, we anticipate also being able to calculate whole-house source emission rates of key pollutants, such as formaldehyde. The source emission rates can then be used in simple mass-balance models to estimate the effect of changing ventilation rates on concentration. This approach for establishing ventilation requirements has been proposed and demonstrated using admittedly limited data obtained for a small set of new U.S. houses (Sherman and Hodgson, 2002). The approach can also be used to estimate the amount of source reduction required to meet available indoor air quality guidelines at specified ventilation rates.

Final Project Report

We believe we could best serve CEC's goals for the study by presenting the results in the form of a series of technical report chapters, which we could relatively easily reduce in length into articles suitable for presentation at scientific conferences and publication in the scientific literature. In this way, the study's findings would be subjected to credible peer review and would be widely accessible. We propose that the three main chapters would generally address the three categories of questions posed under the Project Objectives, i.e, ventilation questions, occupant behavior questions and indoor air quality questions. Many of the other critical components of the study, such as the questionnaires, the selection of the study population, the field operation protocols and data handling would have been presented in interim reports and could be referenced in the final report and/or be included as appendices.

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Table 1. Tentative schedule for completion of major project tasks. Schedule assumes a contract is awarded by the end of 2003. Since many time intensive tasks must be completed in first few months of study, an earlier start date is recommended.

	Characterization of Indoor Air Quality, Ventilation and Ventilation-Related Occupant Behaviors in New California Single-Family Houses																							
	2004												**2005**											
Study task/Milestone	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Prepare background & study period activity questionnaires																								
Prepare & submit documentation for human subjects approval																								
Select study population to city level & finalize recruitment strategy																								
Obtain lists of house developments & unit addresses																								
Develop database & data handling systems																								
Randomize lists of home devel. & addresses; prepare letters																								
Hire & train field staff																								
Conduct training/pilot study																								
Recruitment participants (continuous, until targets met overall and by groups)																								
Conduct questionnaires & field measurements																								
Manage samples & data. Compile interim data																								
Conduct data analysis																								
Submit interim reports																								
Submit draft and final technical report																								

Table 2. Potential list of topics and questions related to owner-occupant behaviors including window operation in multiple seasons (cooling, heating). Questions were obtained from Freeman et al. (1999), Devine (1999) and Weisel et al. (2002).

A. Baseline questionnaire	
Can the majority of the windows in the home be opened?	Yes or No
On average, how many days per month do you open windows and doors in the ____ weather months? (NOTE: Ask for both cooling season, heating season)	(0-31 days or n/a)
On average, how many days per month do you turn on the exhaust fan(s) in the : a) kitchen; b) bathroom?	(0-31 days or n/a)
Does this home have air conditioning (A/C)?	Yes or No
If yes, what type of air conditioning system is used?	(five options)
In what month do you START using A/C?	(12 options)
At what approximate outdoor temperature range do you START using A/C?	(six options, each 5 deg 70 to >95)
What is your approximate thermostat set point when operating the A/C?	(five range options, each 2 deg 65-75)
In what month do you STOP using A/C?	(12 options)
NOTE: Also ask age of home, when moved in, no. of windows and doors, mechanical ventilation system present? (Yes or No)	
B. Study period activity questionnaire	
Were doors at your home left open for ventilation <u>today</u>?	Yes or No
If yes, for approximately how many hours?	(1-24 hrs)
Were doors at your home left open for ventilation during the study?	Yes or No
If yes, for approximately how many hours each day on average?	(1-24 hrs)
Were windows at your home left open for ventilation <u>today</u>?	Yes or No
If yes, for approximately how many hours each day on average?	(1-24 hrs)
If yes, on average how many of the windows were open?	(all,50%,1-2)
Were windows at your home left open for ventilation during the study?	Yes or No
If yes, for approximately how many hours each day on average?	(1-24 hrs)
If yes, on average how many of the windows were open?	(all,50%,1-2)
Did you use your home's air conditioning (A/C) system <u>today</u>? (re: type(s) in baseline Qx)	Yes or No
If yes, for approximately how many hours?	(1-24 hrs)
Did you use your home's A/C system during the study?	Yes or No
If yes, for approximately how many hours each day on average?	(1-24 hrs)
Did you use your kitchen oven exhaust fan <u>today</u>? (re: type(s) in baseline Qx)	Yes or No
If yes, for approximately how many hours?	(1-24 hrs)
Did you use your kitchen oven exhaust fan during the study?	Yes or No
If yes, for approximately how many hours each day on average?	(1-24 hrs)
Did you use your bathroom exhaust fan(s) <u>today</u>? (re: type(s) in baseline Qx)	Yes or No
If yes, for approximately how many hours?	(1-24 hrs)
Did you use your bathroom exhaust fan(s) during the study?	Yes or No
If yes, for approximately how many hours each day on average?	(1-24 hrs)
IF a mechanical ventilation system present, did it operate <u>today</u>?	Yes or No
If yes, for approximately how many hours?	(1-24 hrs)
IF a mechanical ventilation system present, did it operate during the study?	Yes or No
If yes, for approximately how many hours each day on average?	(1-24 hrs)

Table 3. Potential list of topics and questions regarding indoor sources of targeted pollutants (e.g., water use, cooking, cleaning, and materials). Questions were obtained from Freeman et al. (1999), Devine (1999) and Weisel (2002).

A. Baseline questionnaire	
Sources of water for general home use (dishwashing, laundry, garden)? For drinking? For cooking?	
(For each of last three items: Public, private well, only purchased bottled water)	
Does water used for drinking and/or cooking in home receive extra treatment or filtration?	Yes or No
Types of commercial cleaning products, deodorizers used	(X options)
Type(s) of cooking appliances used inside and outside the home	(X options)
Type(s) of heating systems for home or individual rooms	
Type of heating system most frequently used throughout home?	(five options)
In what month do you START using heating system?	(12 options)
At what approximate outdoor temperature range do you START use?	(four options, each 5 deg <50 to 65)
What is your approximate thermostat setpoint when operating heating system?	(five options, each 2 deg 65-75)
In what month do you STOP using heating system?	(12 options)
Does this home have a fireplace and chimney which can be used?	Yes or No
If yes, what do you usually burn in the fireplace?	(3-4 options)
Does this home use incense or scented candles?	Yes or No
NOTE: Also ask type of garage. if attached then a) Doors leading to main living areas? b) Cars usually parked inside?	
B. Study period activity questionnaire	
NOTE: Similar questions to above, but ask about actual use with Yes/No option, and if yes then for how many hours today and on average or exactly each day of study	

Table 4. Proposed measurements and monitoring for a study of indoor air quality, ventilation and ventilation-related occupant behaviors in new CA single-family houses. For measurements, there would be approximately 10% field duplicate samples, 5% field blank samples (10% for ventilation rate), and 5% laboratory control or analytical duplicate samples.

Parameter	Location	Sampling Technique	Sampling Device	Analysis
Ozone	Indoor	Passive	Ogawa 3300 with pad	Commercial
NO_2 and NO_X	Indoor	Passive	Ogawa 3300 with pads	Commercial
Carbon monoxide	Indoor	Passive	LBNL dosimeter[a]	LBNL
Formaldehyde	Indoor/ outdoor	Passive	UMEx 100, SKC	Commercial
VOCs (BTEX & chloroform	Indoor	Passive	3500 OVM, 3M	Commercial, GC/MS[b]
PM2.5	Indoor	Active	PEM with SKC AirChek 2000 pump, U.S. EPA Method IP-10A	Weigh filters at LBNL
Ventilation rate	Indoor	Passive	PFT sources (4/house) & CAT samplers (1-2/house)	Commercial, Thermal desorption GC-ECD[c]
Temperature/RH	Indoor/ outdoor	Continuous	Onset HO8003-02	Manage data as 5-min avg.

a. Apte et al., 1999
b. Gas chromatography/mass spectrometry
c. Gas chromatography with electron capture detection

Table 5. California non-occupational exposure guidelines for formaldehyde.

Organization	Type	Level (ppb)	Level ($\mu g\ m^{-3}$)	Description
CA State Air Resources Board[a]	Govt.	100		Action level
CA State OEHHA[b]	Govt.	75	94	1-h Acute REL[c]
CA State Air Resources Board[a]	Govt.	50		Target level
CA State OEHHA[d]	Govt.	2.4	3	Chronic REL

a. CARB, 1991
b. OEHHA (Office of Environmental Health Hazard Assessment), 2000
c. Reference Exposure Level
d. OEHHA, 2001

Figure 1. Diagram of a possible multi-stage cluster design illustrating the strategy for first three stages to identify and define the population for a study of indoor air quality, ventilation and ventilation-related occupant behaviors in new CA single-family houses. The climate zones, counties, and cities identified in the figure are only illustrative examples.

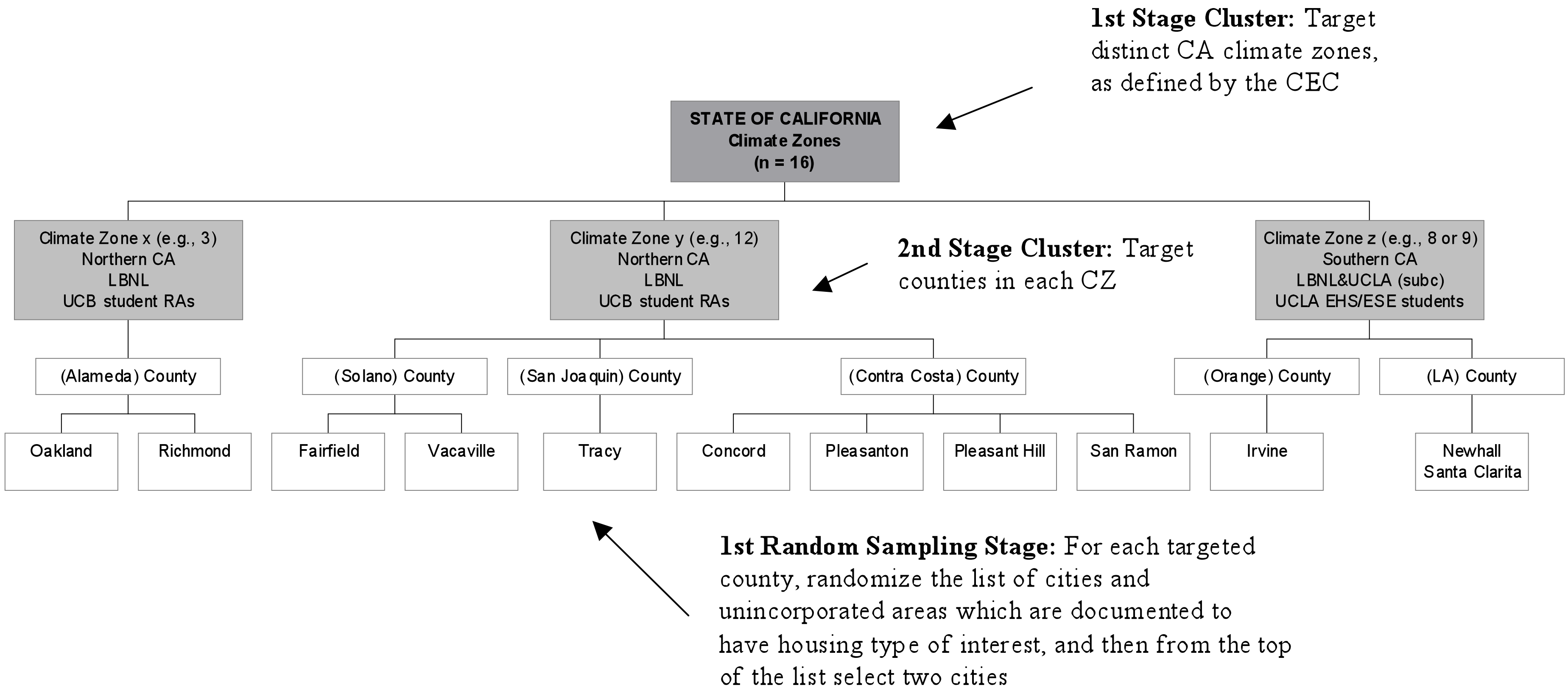

Figure 2. Diagram of the entire selection process to obtain a study sample of new CA single-family houses. The second and third random sampling stages are shown along with the recruitment strategy and eligibility criteria.