California Environmental Protection Agency

Air Resources Board

# PLANNED AIR POLLUTION RESEARCH

## Fiscal Year 2010-2011

**July 2010**

The statements and conclusions in this paper are not necessarily those of the California Air Resources Board. The mention of commercial products, their source, or their use in connection with material reported is not to be construed as either actual or implied endorsement of such products. To obtain this document in an alternative format, please contact the Air Resources Board Disability Coordinator at (916) 323-4916 or 7-1-1 for the California Relay Service. This report is available for viewing or downloading from the Air Resources Board's Internet site at http://www.arb.ca.gov/research/apr/apr.htm.

## Acknowledgments

This report was prepared with the assistance and support of managers and staff from the Research Division, Mobile Source Control Division, Monitoring and Laboratory Division, Planning and Technical Support Division, Office of Climate Change, and Stationary Source Division of the Air Resources Board. We would also like to acknowledge the members of the academic community, government agencies, private businesses, and the public who submitted research ideas.

**Reviewed By:**

Research Screening Committee
Harold Cota, Ph.D. (Chairman)
Dan Costa, Ph.D.
Irva Hertz-Picciotto, Ph.D.
Steven Japar, Ph.D.
Matthew Kahn, Ph.D.
Charles Kolstad, Ph.D.
Chung Liu, D.Env.
Rachel Morello-Frosch, Ph.D.
Suzanne Paulson, Ph.D.
Tracy Thatcher, Ph.D.
Forman Williams, Ph.D.

External Reviewers and Collaborators
Bay Area Air Quality Management District
California Department of Resources Recycling and Recovery
California Department of Transportation
California Energy Commission
California Public Utilities Commission
Coordinating Research Council
Health Effects Institute
National Oceanic and Atmospheric Administration
New York State Energy Research and Development Authority
Office of Environmental Health Hazard Assessment
South Coast Air Quality Management District
United States Environmental Protection Agency

## TABLE OF CONTENTS

## SUMMARY

This report presents the Air Resources Board's planned air pollution research for the fiscal year 2010-2011. Twenty-five projects that support the Air Resources Board's programs are recommended for funding. An additional four projects are offered for consideration, should additional resources become available. This research portfolio is organized by key policy and regulatory drivers: Health Effects and Exposure; Emissions Reductions; Climate Change, Energy Efficiency, and Conservation; Economic Analysis; and Technology Research and Development. Issues related to agriculture and environmental justices are integrated into several of these primary categories.

This annual plan proposes research in the areas listed above, with a significant effort to further inform health impacts of air pollution, develop technologies and behavioral change strategies to reduce emissions of greenhouse gases, improve emission inventories, characterize and assess the behavior of pollutants in the atmosphere, and reduce emissions of conventional air pollutants and their precursors. The total budget for projects recommended for funding is approximately $6.5 million.

## INTRODUCTION

The Air Resources Board (ARB or Board) sponsors a comprehensive program of research addressing the causes, effects, and possible solutions to air pollution problems in California. This research program also provides support for establishing ambient air quality standards. The Board's research program was established by the Legislature in 1971 (Health and Safety Code Sections 39700 et seq.) to develop a better understanding of air pollution in California, including air pollution's effects on health and the environment, atmospheric chemistry and transport of pollutants, and inventory and control of emissions. Several legislative mandates have expanded and further defined the scope of the program in recent years. For example, ARB's growing research interest in climate change issues is reflected by Assembly Bill 2991 (Nuñez, 2008), which expanded membership of ARB's Research Screening Committee to include two experts on climate change.

ARB's research portfolio comprises collaborative studies involving a variety of scientific disciplines and approaches. Some of these studies are long-term and build on unique data sets, while others address specific implementation or knowledge gaps as single modules. ARB funds niche projects that provide crucial input to California's air quality regulatory programs and may be unlikely to receive support from other funding agencies. In many cases, ARB technical staff play an active role in the research that extends far beyond contract management.

***Objective of the Research Program.*** The goal of the research program is to provide timely scientific and technical information that will help the Board and local air pollution control districts to make sound policy decisions and effectively implement air pollution control programs in California. Specifically, this plan supports ARB's mission to protect public health based on a sound scientific understanding of health effects and exposures; continue developing and implementing strategies to reduce greenhouse gas emissions and energy consumption; develop effective strategies to safeguard health and welfare against adverse impacts of ambient air pollution; and support development of technologies and non-technological strategies that address multiple priorities related to air quality.

***Process for Developing this Research Plan.*** Every year the Board sends out a public solicitation inviting and encouraging the public to contribute ideas for project consideration. Members of the public, the academic community, and ARB staff submit research ideas. To aid in the evaluation, the Board's Executive Officer has established interagency committees, led by ARB staff, to review research ideas. These interagency review teams comprised, in addition to ARB staff, experts from state agencies with related research priorities and responsibilities as well as experts from other state, air district, federal, and non-profit institutions with scientific research or regulatory authority in areas of policy relevance to ARB. In response to this year's solicitation, approximately 150 research ideas were submitted. Proposed projects were examined for relevance to regulatory questions facing the Board, scientific and technical merit, and opportunities to leverage State resources through co-funding. Proposals were modified as necessary to

support ARB's goals. Reviewers then prioritized candidate projects with regard to urgency, cost-effectiveness, and likelihood to succeed. The Board's scientific external review committee, the Research Screening Committee (RSC), which was established by Health and Safety Code Section 39705, reviews candidate projects. A list of projects recommended for funding, as well as projects to consider pending availability of resources is compiled based on discussions between interagency review committees, feedback from ARB's divisions, and comments from the RSC as well as an agricultural stakeholder outreach working group. This list of recommended projects is submitted to the Executive Research Review Committee, whose members are the Executive Officer, his three deputies, and the Chief of the Research Division. The Executive Research Review Committee reviews all of the proposed projects and modifies the draft list of projects recommended for funding based on ARB's most pressing policy and regulatory needs. Finally, the RSC reviews the selected projects and recommends the Plan to the Board.

***Implementation of the Plan.*** The next step for research concepts approved in the plan is their development into full research projects. The submission and selection of an idea does not guarantee a resulting contract for the submitter. Rather, ARB is required to consider public California universities for expertise to execute these projects. If the universities do not possess the expertise, then a public solicitation is issued or a sole source contract is awarded. A list serve distributes updates on research activities. To subscribe to the list serve, please visit: http://www.arb.ca.gov/listserv/listserv_ind.php?listname=research.

***Research Budget.*** The twenty-five recommended projects total approximately $6.5 million. An additional four projects totaling approximately $1.3 million may be considered if additional resources become available. Allocations for the projects recommended for funding are distributed among key research areas as follows:

| RESEARCH CATEGORY | BUDGET |
|---|---|
| Health Effects and Exposure | $1,519,439 |
| Emissions Reductions | $2,853,000 |
| Climate Change, Energy Efficiency & Conservation | $1,315,000 |
| Economic Analysis | $480,000 |
| Technology Research & Development | $376,000 |
| TOTAL | **$6,543,439** |

***Interagency Coordination.*** The Research Division works with other California government agencies to ensure that projects are non-duplicative, to identify opportunities to leverage resources, and to maximize the utility of research results. To foster coordination, staff at different agencies share information and solicit input from other agencies at all stages of the research process, including proposal review, updates on research progress, and final reports. Furthermore, the Climate Action Team has

established a Research Subgroup to coordinate the State's climate change research. Starting in fall 2010, this Subgroup will hold annual meetings where State Agency research staff will display the products of research projects, summarize their on-going and planned research activities, and identify opportunities for collaboration. The CAT Research Working Group also maintains a database of State-funded climate change research. ARB, in collaboration with the California Council of Science and Technology, is compiling a database of climate change research in California's public and private universities, national laboratories, and State agencies. This publicly available tool is designed to help the State identify intellectual resources, in the form of principal investigators, ongoing or complete research, and databases, that can facilitate cost-effective attainment of climate change goals.

***Project Co-Sponsorships*.** ARB is continually seeking co-funding opportunities and other ways to leverage the State's research dollars. This effort allows the ARB to be part of projects and studies that may otherwise lie beyond the state's fiscal reach. ARB has successfully worked with other research organizations and has participated in multi-million-dollar collaborations.

***Summaries of Past Research.*** Projects completed since the beginning of 1989 are summarized in the Research Division's publication, *Air Pollution Research*, available at www.arb.ca.gov/research/apr/past/past.htm. Research Division's final reports are available at the same web site.

***Organization of the Research Plan.***
This research plan is organized according to key research categories that support the Board's mission: Health Effects and Exposure; Emissions Reductions; Climate Change, Energy Efficiency, and Conservation; Economic Analysis; and Technology Research and Development; with issues related to agriculture and environmental justice integrated into several of these primary categories. For each research area, an overview indicates primary policy drivers, links to ARB's mission, ongoing research efforts in the area, and research and knowledge gaps that need to be addressed. These contextual overviews are followed by the projects recommended for funding as well as those that may be considered if additional funds become available.

The proposed research projects are not intended to be exhaustive or exclusive. Unanticipated opportunities, unique or innovative study approaches, or urgency may lead to consideration of other projects.

# OVERVIEWS OF RESEARCH AREAS

## *Health Effects and Exposure*

**Context**

The health impacts of particulate matter (PM) air pollution have been confirmed by extensive studies conducted at many universities and institutions world-wide. The United States Environmental Protection Agency (U.S. EPA) recently released a comprehensive review of the scientific literature on the health and welfare impacts of particulate matter. That review included consideration of hundreds of epidemiological, toxicological and human exposure studies, and it concluded that there is a causal relationship between long-term PM2.5 exposure and mortality and for cardiovascular effects. The U.S. EPA further concluded that there is a likely causal relationship between long-term PM2.5 exposure and respiratory effects. Although the ARB has made considerable progress in reducing PM emissions from motor vehicles and other sources, and consequently reducing the level of adverse health effects of PM, the burden of PM exposure remains particularly acute, in part because California is home to two of the worst non-attainment areas in the U.S. with regard to federal 2006 PM2.5 standards.

Substantial progress has been made in understanding the mechanisms of PM toxicity, as well as the magnitude of the associated mortality risk. However, ARB must continue to improve its understanding of the specific components and sources of PM that are responsible for health burdens, as well as illuminate the mechanisms that cause adverse health impacts, particularly in vulnerable populations. This improved understanding will foster development of increasingly targeted and cost-effective regulations.

ARB's health and exposure research also targets indoor air quality because the indoor concentration of many air pollutants exceeds that of the outdoor levels, often elevating Californians' exposures to unhealthful levels of those pollutants. Previously, ARB's indoor air quality research focused on gaining a better understanding of indoor sources and exposures (especially for toxic air contaminants), the relationship between indoor and outdoor air pollution, and how building factors affect indoor pollutant concentrations and exposures. Current and planned research is focused on improved indoor source emission measurement techniques and the effectiveness of various mitigation approaches for reducing indoor concentrations and exposures. ARB's 2005 *Report to the Legislature: Indoor Air Quality in California* identified high priority indoor source categories requiring mitigation, including indoor air cleaning devices that emit large quantities of ozone, and building materials that produce high levels of formaldehyde and other volatile organic compounds (VOCs) indoors. ARB's pioneering research provided the key information that identified the need for recent regulation of these sources, but additional information is needed. For example, new technologies in indoor air cleaning devices require more sophisticated emissions measurement and mitigation techniques. Thus, a top priority is measuring pollutant emissions from indoor sources and investigating strategies for reducing individuals' levels of exposure to those pollutants.

**Policy Drivers**

- The Children's Environmental Health Protection Act (SB 25, Escutia, 1999)

- Reviewing and evaluating Ambient Air Quality Standards (Title 17 of the California Health & Safety Code, Section 39606)
- Diesel Risk Reduction Plan
- Regulation of Ozone Emissions from Indoor Air Cleaning Devices (California Health & Safety Code, Sections 41985 et seq.)

**Research Themes**

- *Particulate matter toxicity*. Public health risk from air pollution is dominated by exposure to PM. Much progress has been made over the last decade documenting the serious nature of the health risk from exposure to particles; now, research is needed to determine the relative toxicity of the components of the mixture of ambient particles. Furthermore, the biological mechanism of toxicity, which is just now coming to light, needs to be investigated. Research on the characteristics of particles, such as size, chemical composition, and interaction with other pollutants, are crucial in designing smarter, more targeted regulations, while providing adequate protection of public health and the environment.
- *Vulnerable populations*. As part of its mission, ARB investigates the health effects of air pollution in support of ambient air quality standards that are adopted to protect the health of all Californians, including sensitive sub-groups and those living in disadvantaged communities. Sensitive sub-groups of interest include children, the elderly, and those with chronic health conditions, such as asthma, cardiovascular and pulmonary disease.
- *Indoor air quality*. A top priority is measuring pollutant emissions from indoor sources and investigating strategies for reducing individuals' levels of exposure to those pollutants.

## Recommended for Funding

*Particulate Matter Toxicity*

**Season- and location-specific systemic health effects of ambient PM**

Problem: A diverse and increasingly sophisticated body of epidemiologic evidence associates environmental particulate matter with asthma as well as cardiovascular morbidity and mortality, but less is known regarding the biological mechanisms as well as the specific PM components that are responsible for ill health. Most studies focus on urban particle sources and do not distinguish between regional differences in particle composition and potential pulmonary or systemic health outcomes. Stronger support for source-apportioned regulation depends on correlating source specific composition with health effects.

Objective: This project will use a mouse model to correlate PM composition, season, and location (urban versus rural) with biologic markers relevant to cardiovascular disease. Results will provide a biological link between epidemiologic studies and a principal health outcome of PM exposure, and will provide critical information on toxicity of PM from different sources that will help to inform future source-specific regulations.

*Proposed funding level: $266,298*

**Biological activity of near-freeway particulate and gases**

Problem: Epidemiological studies have shown associations between exposure to near roadway air pollutants and mortality and other adverse health outcomes, and a large

number of in vitro and animal studies have shown that particulate matter has pro-oxidant activity relevant to the pathogenesis of these conditions. However, no study has examined how changes in the proximity to major roadways may impact the biological activity of particles. This project addresses that missing link and is an opportunity to identify the components of traffic-related pollutants potentially responsible for adverse health effects.

Objective: This proposed roadway gradient study will evaluate the seasonal and spatial variation in both gas and particle phase air pollutants. To link the physical/chemical characteristics of pollutants to biological activity, investigators will use state-of-the-art cellular assays to examine the role of chemical composition in determining the pro-oxidant, electrophilic, allergic, and inflammatory activity of ambient aerosols. Findings will promote our understanding of the causal relationship between exposure and health outcomes as well as clarify the spatial pattern of risk, and may guide development of regulatory and public health policy.

*Proposed funding level: $300,000*

*Vulnerable Populations*

**Risk of pediatric asthma morbidity from multipollutant exposures**

Problem: Asthma morbidity has been associated with fluctuations in daily concentrations of ambient air pollution, most strikingly with traffic-related air pollutants. However, the combined importance of local exposure to traffic-related ultrafine particles and regional exposure to ozone, as well as organic components of PM2.5, is largely unknown. This lack of information is due to the difficulty in estimating the exposure profiles of individuals at risk.

Objective: Investigators will use PM concentrations predicted by regional air quality models to study the relationship of asthma morbidity in over 7,500 children to exposure to primary organic aerosol (POA), which is directly emitted from sources, and secondary organic aerosol (SOA), which forms in the atmosphere from precursor emissions. The findings from this research will clarify the roles that components of complex urban air pollution play in producing adverse asthma outcomes in children.

*Proposed funding level: $285,000*

**Investigation of persistent immune effects of acute PM exposure during early life and development of a biomarker for lung function decline**

Problem: Although epidemiological studies suggest that there are life-long impacts of childhood air pollution exposures, the biologic mechanisms that mediate reduced lung function growth are not fully understood, and the phenomenon is difficult to study due to a lack of minimally invasive biomarkers. In addition to compromising lung development, preliminary data suggest that childhood exposures to air pollution may alter immune system development. The relationship between lung function growth and immune system development may offer a minimally invasive means of monitoring impacts of childhood air pollution exposures.

Objective: The proposed study will investigate the impact of environmental air pollutant exposure on immune system development and lung function growth in a cohort of rhesus monkeys that were born at the California National Primate Research Center, just prior to significant PM exposure from the Trinity and Humboldt County wildfires in July 2008. These fires led to air pollution levels significantly above ambient air quality standards that lasted for several weeks, which coincided with a period of rapid lung

growth in the exposed animals. The similarities between humans and rhesus monkeys in lung and immune system growth and development coupled with the cohort's inadvertent exposure to high levels of air pollution during a critical developmental period provides a unique opportunity to probe the mechanisms by which air pollution influences lung and immune system growth and development in children. The endpoints to be studied require minimally invasive procedures, and include lung function tests and blood draws that will provide the information needed while not harming the subject animals.
*Proposed funding level: $268,141*

*Indoor Air Quality*

**Evaluation of secondary pollutant emissions from portable air cleaners**

Problem: Although ARB is implementing a regulation to limit ozone emissions from portable indoor air cleaners such as electrostatic precipitators (ESPs), ionizers and ozone generators (OGs), some of these devices, including newer technology air cleaners designed to produce less ozone, may also cause the production of formaldehyde and other pollutants through their operation or from reaction of their emissions with other constituents of indoor air. Thus, the current regulation to limit ozone emissions from portable indoor air cleaners may not suffice to safeguard indoor air quality.

Objective: This research will evaluate the emission of indoor pollutants by devices commercialized as portable air cleaners in California, with emphasis on a new generation of equipment integrating several technologies that include photocatalytic oxidation. Both primary emissions and those formed by reaction in the indoor environment will be determined in realistic indoor conditions, to assess the potential for exposure and possible health risks. Results will help the State assist the public in making informed decisions when purchasing and using these devices, and may help determine whether such emissions require regulation.
*Proposed funding level: $400,000*

## Recommended if Additional Funding Available

*Particulate Matter Toxicity*

**Toxicity of fresh and aged semi-volatile PM**

Problem: Many Californians live in nonattainment areas for PM2.5, and the contribution of aged pollution emissions from sources such as motor vehicles is significant to PM concentrations. However, less is known about the toxicity of aged emissions than is known for fresh tailpipe emissions. Within seconds of leaving the tailpipe, there are dramatic changes in gas-particle partitioning of semivolatile organic materials. These changes transform aerosol mass and chemical composition, but more importantly, they considerably alter the toxicity of the emissions.

Objective: The proposed two-phase research study will investigate the toxicity of fresh and aged motor vehicle emissions. This project will provide needed information on the atmospheric evolution of fresh vehicular emissions and their physico-chemical characteristics, transformation, and resulting toxicity. This knowledge will be vital in the development of cost-effective strategies to protect the public from toxic sources.
*Proposed funding level: $300,000*

*Vulnerable Populations*

**Traffic-related pollution, DNA methylation and asthma in children living near sea ports**

Problem: Asthma has a strong genetic basis, and genetic variants contribute to increase asthma susceptibility to exposures from traffic-related pollution. A growing body of evidence also suggests an epigenetic component in asthma susceptibility: air pollution may alter gene expression through effects on DNA methylation.

Objective: The proposed study will use a novel approach to generate new data that will improve understanding of the linkages among traffic-related pollution, DNA methylation and asthma progression in children. Results will also shed light on the impact of reductions in traffic-related pollution in the vicinity of the part of Long Beach due to ARB's implementation of the Goods Movement Emission Reduction Program on asthma progression and important epigenetic influences on asthma progression.

*Proposed funding level: $550,000*

*Indoor Air Quality*

**Zero-energy air purification materials to reduce the exposure of Californians to harmful air pollutants**

Problem: Ozone is both a health-damaging air pollutant and a driver of indoor chemistry that leads to the formation of oxidized reaction products, some of which are toxic or irritating. Indoor exposures are also responsible for 70% of cumulative exposure to a wide range of organic hazardous air pollutants (typically volatile organic compounds or VOCs). Indoor controls are a potential, but largely unexplored, strategy to reduce population exposures to ozone and its reaction products, as well as to organic hazardous air pollutants.

Objective: This study will explore the use of zero energy air purification building materials (e.g., wall materials) for substantially reducing population exposures to ozone, ozone reaction products, and organic hazardous air pollutants. If successful, this novel approach to exposure reduction could substantially reduce people's exposures from both indoor and outdoor emissions, when source controls do not exist or are insufficient to reduce pollutant levels below levels of health concern.

*Proposed funding level: $254,205*

## *Emissions Reductions*

**Context**

Over the past four decades, ARB's emissions reductions strategies have yielded many improvements in air quality. For example, since the 1970's, aggregate tailpipe emissions of CO from on-road vehicles have been reduced by nearly 90%, and emissions of $NO_X$ have been reduced by nearly one-half, despite substantial population growth and a more than doubling of vehicle-miles-travelled. However, California's topography and meteorology, compounded by continued population growth and a warming climate, render it vulnerable to poor air quality. Much of the State still struggles to meet air quality standards for ozone and particular matter (PM). Attaining air quality standards that protect public health rests on the best possible science to guide effective planning and implementation of emissions reductions strategies. In particular, meeting the U.S. EPA's current PM2.5 standards will require that the State's planning and implementation strategies are informed by accurate emissions inventories and partitioning models of primary PM as well as improved models of secondary aerosol formation processes and transport dynamics.

**Policy Drivers**

- Development of emission targets and State Implementation Plans for ozone.
- Development of emission targets and State Implementation Plans for PM.
- Improved inventory estimates of conventional air pollutants and greenhouse gases (GHG).

**Research Themes**

- *Agriculture*: Criteria pollutant and GHG emissions from several agricultural sources, such as VOC emissions from dairy silages and nitrous oxide from manure management, need to be developed or refined to support decision-making by the Board. Research projects will be crafted to support improvements to the inventory as well as identification and development of best practices for reducing emissions.
- *Vehicular emissions reductions*: Near-term emissions reductions with the current vehicle fleet are possible through improved operations and management. These strategies will complement existing rules requiring progressively cleaner heavy-duty diesel engines for the California fleet, and will reduce emissions of greenhouse gases as well as conserve energy.
- *Atmospheric chemistry*: Continued progress in reducing Californians' exposures to air pollution requires resolving the chemical and physical mechanisms responsible for transformation of emissions to ambient concentrations. Priority research gaps include investigation of atmospheric chemistry of particles, including mechanisms for formation of reactive oxygen species, aerosol partitioning and implications for PM concentrations, and quantifying the ammonia slip and eventual by-products associated with selective catalytic reduction for $NO_X$ control;
- *Emissions inventory*: To optimize the development of cost-effective strategies for protecting public health, emissions inventories must be complete, up-to-date, and accurate. Current research needs include refinement of the emissions inventory associated with vehicular sulfate emissions, in-use tailpipe PM emissions, and organic aerosols; as well as improving ARB's source apportionment of the methane

emissions inventory. Due to its relatively short atmospheric lifetime coupled with strong climate forcing properties, ARB recognizes the potential for cost-effective, near-term, substantial climate benefits from reducing methane emissions.

- *CalNex*: In the summer of 2010, a large-scale multi-agency field study was conducted in California to better understand the emissions, transport, and transformation of conventional and climate change air pollutants. To leverage the results of this field work for maximum policy benefit requires a timely analysis and synthesis of the very large dataset collected.

## Recommended for Funding

*Agriculture*

**Characterization and mitigation of volatile organic compound emissions from dairy silage sources**

Problem: Dairies are a major source of volatile organic compound (VOC) emissions in California and published studies suggest dairy cow feed or silage is an important factor in these emissions. However, the impact of silage on the magnitude and nature of VOC emissions is not well understood.

Objectives: This project will: (1) characterize silage production and management practices in California dairies; (2) evaluate effects of different ensilage practices on VOC emissions; (3) determine the potential for producing VOC's (in particular alcohol and aldehydes) emissions from different silages; and (4) delineate "best practices" for reducing or preventing the generation of alcohols and aldehydes during the ensiling process and consequently reducing their emissions.

*Proposed funding level: $300,000*

**Developing, validating and implementing a process modeling system for California agriculture greenhouse gas inventories**

Problem: Despite their significant contribution to livestock GHG emissions, nitrous oxide ($N_2O$) emissions were excluded from the California Climate Action Registry's (CCAR's) livestock project reporting protocol, which was developed to support manure management, one of ARB's AB32 Early Action measures. CCAR anticipates expanding the protocol to include GHG reductions beyond methane capture and destruction from biogas systems.

Objectives: Project objectives include: (1) expansion of existing field measurements of $N_2O$ emissions from major sources in California's dairies, (2) further testing of UCD's Manure-DNDC model to quantify model uncertainties, (3) assessment using full process model versus detailed, regional/soil specific emission factors for estimating both baseline and project $N_2O$ emissions from manure management, and (4) work with CCAR, ARB, Western United Dairymen, Sustainable Conservation, the San Joaquin Valley Air Pollution Control District, and an advisory panel to deliver an updated livestock reporting protocol.

*Proposed funding level: $300,000*

*Vehicular Emissions Reductions*

**Investigation of Combined Aerodynamic Modifications to Reduce Emissions from the Current Heavy Duty Fleet**

Problem: ARB's recently adopted tractor-trailer GHG rule requires that new and existing long-haul box-type trailers, as well as the tractors that pull them, be equipped with U.S. EPA Smartway-approved aerodynamic technology. However, little work has been done to investigate and quantify the benefits from combinations of multiple devices used simultaneously..

Objective: The proposed research will develop an evaluation protocol as well as test aerodynamic devices in multiple combinations on multiple platforms for increased reductions of greenhouse gases from on-highway trucks. Research results research will support innovative GHG emissions reductions and fuel-saving strategies that could be implemented with California's current heavy duty fleet.

*Proposed funding level: $300,000*

*Atmospheric Chemistry*

**Probing the intrinsic ability of particles to generate reactive oxygen species**

Problem: Oxidative stress caused by reactive oxygen species (ROS) is a leading hypothesis for the mechanism by which particulate pollution contributes to a range of illnesses, including asthma and cardiovascular mortality. ROS are generated within the body in response to inhalation of PM, but the "exogenous" ability of the particles themselves to generate ROS may also be important.

Objectives: This research will: (1) determine the strength of reactive oxygen species (ROS) production intrinsic in ambient particles, (2) probe sources and relative strengths of ROS production via (speciated) transition metals and quinones, (3) probe the balance between $H_2O_2$ and OH and the underlying mechanism(s) of ROS generation, and (4) clarify the sources of quinones in particles.

*Proposed funding level: $260,000*

**Understanding primary organic aerosol volatility at atmospherically realistic concentrations for SIP analysis**

Problem: Details of primary organic aerosol partitioning must be understood to predict the benefits of emissions control programs contained in the SIP as well as the impact of climate change on atmospheric organic aerosol pollution. Recent emissions tests have determined that primary organic aerosol generated from combustion sources behaves like a series of semi-volatile compounds when particulate phase concentrations range between 100 $\mu g/m^3$ and 10,000 $\mu g/m^3$.

Objective: The study will identify the dominant partitioning mechanism for primary organic aerosol emitted from diesel-powered and gasoline-powered vehicles at atmospherically realistic concentrations in the ranging from 5 to 30 $\mu g/m^3$. Results will provide input for regional airshed models that seek to predict changes to ambient organic aerosol concentrations in the presence of emissions control programs and/or climate change.

*Proposed funding level: $300,000*

**Quantification of ammonia slip from SCR-equipped vehicles and estimation of secondary aerosol formation potential**

Problem: As technologies such as Selective Catalytic Reduction (SCR) are developed to control conventional air pollutant emissions, care must be taken that operation of the new technologies does not produce new emissions that exacerbate air quality. SCR is becoming common for controlling oxides of nitrogen ($NO_X$) emissions from diesel vehicles. Excess ammonia that does not react with $NO_X$, called "ammonia slip", is emitted in the atmosphere. Atmospheric ammonia is very reactive, causing the formation of ammonium sulfate ($(NH_4)_2SO_4$) and ammonium bisulfate ($NH_4HSO_4$), two of the most significant types of PM in California. Ammonia slip can also react with $NO_X$ to form ammonium nitrate if the SCR catalyst efficiency decreases after prolonged usage. In addition, ammonia in other forms such as free ammonia, ammonia salt, PM generated from ammonia salt, and secondary organic aerosol in the atmosphere are serious health and environmental hazards.

Objective: This investigation will quantify ammonia slip emitted from two SCR-equipped light duty vehicles operating at high, low, and transient modes; and investigate the correlation between ammonia slip and its effect on PM formation as well as PM mass emissions.

*Proposed funding level: $140,000*

**Development of innovative instrumentation to enable investigation of the relationship between $SO_2$ and sulfate**

Problem: Sulfur is an important component of combustion and lubricant-derived particles. Sulfate levels in vehicle exhaust particulates can be readily measured, but it is important to understand the relative contribution between combustion and oil-derived particles and conversion rates of sulfur dioxide ($SO_2$) to sulfate ($SO_4$). Current instruments are not capable of measuring the very low sulfate concentrations typical of new vehicles. Detection limits in the parts per billion range are needed to measure the $SO_2$ contribution from current and future model year vehicles.

Objective: The objective of this research is to construct, test and provide to ARB a differential optical absorption spectrometer (DOAS) that can measure down to 10 ppbV in real time and determine a mass balance between $SO_2$ and sulfate. Training for ARB's technical staff will also be provided as part of this program so they can run this state-of-the-art instrument independently.

*Proposed funding level: $90,000*

**Development of a high quality proportional gravimetric PM system for in-use emissions measurements at low emissions levels**

Problem: As vehicular PM emissions continue to be reduced, it is increasingly difficult to reliably measure in-use PM emissions, and protocols based on particle number or portable emissions measurement systems (PEMS) have not been satisfactory for gauging PM mass emissions rates. For example, comparisons of PEMS-based PM measurements to gravimetric reference methods reveal significant disparities, with deviations on the order of 100%. This poor correlation does not indicate faulty real-time instruments, but is the result of different measurement principles.

Objective: This research will develop and evaluate a new gravimetric-based system designed specifically for in-use conditions including on-highway, marine, and non-road

applications. The system will satisfy ARB's need for in-use PM measurements that are collected with PEMS but comparable to gravimetric reference methods.
*Proposed funding level: $300,000*

**Extended analysis of the CARES aerosol chemistry data to characterize the sources and processes of organic fine particulate matter**
Problem: Although organic aerosol represents a major mass fraction of fine particles in California, the ability of current air quality models to simulate ambient organic aerosol concentrations is limited by poor characterization of organic aerosol sources, formation mechanisms, and evolution processes. In particular, mechanisms by which organic aerosol is formed in the atmosphere requires clarification to improve model performance.
Objective: ARB funding will leverage a Department of Energy-funded project (aerosol characterization during CARES) to allow for advanced analyses to characterize the sources, formation, and atmospheric evolution of organic aerosol based on field data from the Sacramento and foothills region.
*Proposed funding level: $155,000*

*Emissions Inventory*

**Methane source apportionment with stable isotope tracing**
Problem: Methane is a powerful greenhouse gas with a global warming potential roughly 25 times that of $CO_2$ but a substantially shorter atmospheric lifetime, on the order of decades. Reducing methane emissions in a cost-effective way requires understanding how much is produced by different sources such as petroleum production, landfills, wastewater treatment, and agricultural fields and livestock.
Objective: This project will enhance ARB's methane monitoring network by using stable isotopes of methane to differentiate emission sources, thereby facilitating source apportionment. Research results will help prioritize, achieve, and verify methane emissions reductions. *Proposed funding level: $128,000*

**Improving California's GHG emission inventory through ground-referenced remote sensing of fossil fuel industry emissions, and biological methane and carbon dioxide emissions**
Problem: Methane's radiative properties and relatively short atmospheric residence time suggest that climate benefits of methane emissions reductions can be more cost-effective than $CO_2$ emissions reductions. However, effective regulation is hampered by discrepancies between top-down (or atmospheric inversion) and bottom-up (inventory) approaches for methane budget estimation; these discrepancies suggest emission inventory underestimation. Uncertainties in industrial emissions of methane from the fossil fuel industry, as well as substantial seasonal, spatial, and diurnal variability in biological methane emissions, warrant further investigation.
Objective: The study will leverage a successful NASA-funded satellite-based effort using a ground-based sensor to derive an improved estimate for emissions from terrestrial and marine fossil fuel production facilities, refineries, and biological sources using a combination of remote sensing and ground reference measurements.
*Proposed funding level: $330,000*

*CalNex: Field Research to Inform Policy*

**Synthesis of policy-relevant findings from the CalNex 2010 field study**

Problem: The field phase of the joint ARB-NOAA CalNex 2010 field study, which leveraged vast scientific and intellectual resources to gather hitherto unavailable data that illuminate atmospheric processes and emissions relevant to air quality and climate change, was completed during the summer of 2010. It is important to now ensure that the results of that study are made fully available to California policy makers who must deal with air quality and climate change issues. The fieldwork was planned to address a number of scientific questions that were formulated to guide the study planning. The questions address many specific and general science needs that are required to improve policy responses to air quality and climate change issues.

Objective: The goal of the proposed work is to synthesize the results of ongoing, multi-agency, highly leveraged CalNex 2010 analyses to answer an array of science questions that directly support air quality policy, planning, and implementation. Results will be delivered in a timely fashion and in a form most useful to policy makers.

*Proposed funding level: $250,000*

## *Climate Change, Energy Efficiency and Conservation*

**Context**

California's legislative policy and executive orders have established significant energy and environmental initiatives related to climate change. The state is widely recognized for innovations in the utility sector and building efficiency. For example, Executive Order S-20-04 related to state building energy efficiency requires 20% reductions in grid-based electricity purchases for state-owned buildings by 2015. More recently, SB 1368 (Perata, 2006) mandated a greenhouse gas (GHG) emissions portfolio standard for baseload electricity generation.

California has led the nation with respect to tailpipe emissions reductions of criteria pollutants for four decades, and with the passage of AB 1493 (Pavley) in 2002 the state expanded its successful emissions reduction programs to include vehicular emissions of GHGs. The Low Carbon Fuel Standard introduced by Executive Order S-1-07 and adopted by the Air Resources Board as an AB 32 Discrete Early Action in June 2007 represents another approach to reducing vehicular tailpipe GHG emissions by reducing the carbon content of fuels.

Legislative efforts to support scientific, administrative, legal, and technical dimensions of climate policy date back to 1988, when the California Energy Commission (CEC) was charged with the task of studying the effects of climate change on California. Since year 2000, when SB 1771 (Sher) established the California Climate Action Registry as a nonprofit that records and registers voluntary emissions reductions, SB 527 (Sher, 2001) and SB 812 (Sher, 2002) have broadened the technical scope and refined administrative aspects of emissions reporting and reduction protocols. More recently, AB 32 tasked ARB with the duty of reducing the state's GHG emissions to 1990 levels, and E-S-05 set a goal of 80% emissions reductions of GHG pollutants by 2050.

California's continued leadership in building energy efficiency, reducing transportation-related emissions, and conserving as well as greening its electricity resources require continued research to aid development and evaluation of voluntary strategies in the residential and building sectors.

**Policy Drivers**

- SB 375 (Steinberg), Sustainable Communities Strategy (2008). *Requires regional planning to incorporate land-use and related strategies to reduce GHG emissions from automobiles and light trucks*.
- SB 97 (Dutton), CEQA: Greenhouse gas emissions (2007). *Incorporate guidelines for GHG emissions impacts into CEQA*.
- AB 32 (Nuñez), California Global Warming Solutions Act of 2006. *Reduce greenhouse gas emissions to 1990 baseline by 2020.*
- SB 1368 (Perata), Electricity: emissions of greenhouse gases (2006). *Establish greenhouse gas emission performance standard for baseload generation*.
- AB 1925 (Blakeslee), Carbon sequestration (2006). *Identify technical readiness and barriers to geologic carbon sequestration*.

- AB 1493 (Pavley), Vehicular emissions: greenhouse gases (2002). *Regulate greenhouse gas emissions from cars and light trucks, incentivizing earlier actions through the California Climate Action Registry*.
- Executive Order S-3-05 establishing greenhouse gas emissions reductions targets.
- S-20-04, State building energy conservation. *Requires reductions in electricity purchases for state-owned buildings*.
- SB 1771 (Sher), Greenhouse gas emission reductions: climate change (2000). *Establishes the California Climate Action Registry as a nonprofit that records and registers voluntary emissions reductions*
- AB 1440 (Sher), Statewide emissions inventory and climate study (1988). *Directed CEC to assess global warming impacts on California's energy supply and demand, economy, environment, agriculture, and water supplies; to recommend measures for avoiding, reducing, and addressing impacts; and to develop a statewide GHG inventory*.

**Research Themes**

- *Built Environment*: A large portion of the State's energy consumption is associated with the built environment, for example, electricity and natural gas usage in buildings as well as transportation patterns incurred by land-use decisions. Forward-thinking research investigating this sector will help ARB lighten the energy demand and the carbon footprint of California's built environment, where decisions made today will impact emissions for decades to come.
- *Voluntary Emissions Reductions Strategies*: As articulated in the AB 32 Scoping Plan, the State's success in meeting its climate goals will depend in part on voluntary emissions reductions. Identification and characterization of potential GHG emission reduction strategies will help provide Californians with the resources they need to reduce their GHG emissions through cost-effective and substantive voluntary efforts.

**Recommended for Funding**

*Built Environment*

**Developing databases to estimate California-specific climate forcing benefits of cool roofs**

Problem: Solar-reflective cool roofs decrease air conditioning load, thereby saving electricity and reducing $CO_2$ emissions. By reflecting sunlight back into space, cool roofs can have an additional cooling effect. However, limited information on the spatial resolution of albedo and lack of site-specific urban attributes limit our ability to assess the benefits of widespread deployment of cool roofs and pavements and the extent to which roofs and pavements can be made more reflective.

Objectives: To support an accurate assessment of the climate benefits of cool roofs and cool pavements in California, this research will provide a database of spatially resolved urban attributes coupled to satellite data portraying irradiance and albedo. Results from this effort will support quantification of climate impacts of cool surfaces as well as life cycle cost analyses used to guide California building energy efficiency standards (Title 24) as well as criteria used by the California Department of Transportation, county, and local municipalities to select paving materials.

*Proposed funding level: $250,000*

**The role of land use planning in reducing residential energy consumption and GHG emissions**

Problem: Approximately 20% of California's household GHG emissions are related to heating and cooling needs, which are partly a function of house size and orientation, and are therefore strongly tied to land use planning decisions. The few academic studies that have examined residential energy use as a function of urban form indicate that residents living in high density urban centers emit 20 to 50 percent fewer greenhouse gases from heating and electricity usage than residents of low density suburbs. However, these studies have relied upon data sets created by national energy agencies, rather than more disaggregated state- or local-scale data that more accurately reflects local climatic conditions in California.

Objective*:* This research will: 1) investigate the relationship between land use planning factors and residential energy use in California's various climate zones, while controlling for other factors; and 2) develop a spreadsheet modeling tool that analyzes residential energy use within California climate zones as a function of land use planning factors*.* Findings will directly support achievement of AB 32's Green Building Strategy as well as complement an existing ARB-funded project to delineate the relationship of land use planning variables to vehicle miles traveled (VMT) and transportation energy consumption, ultimately supporting a variety of local and regional planning processes.

*Proposed funding level: $100,000*

**Development and evaluation of energy-efficient approaches to keeping building occupants cool using room air motion**

Problem: A significant portion of California's residential and commercial energy demand is devoted to keeping building occupants comfortable in warmer areas of the state, and the demand for thermal comfort will increase as climate change gains momentum. Moving air through low-power fans or using natural ventilation are strategies for achieving thermal comfort without increasing compressor-based cooling. Former heating and air conditioning standards, which were changed based on findings that large majorities of office occupants prefer increased air movement, discouraged exploration of these cost-saving strategies that address the need to adapt to, as well as mitigate, climate change.

Objective: The project will enable strategies to reduce compressor-based cooling in office buildings through the use of fan-powered air movement by: 1) testing combinations of nozzles and propeller fans mounted on or in office furniture, partitions, and ceiling panels; 2) characterizing the physiological cooling effect for these combinations and quantifying how much the ambient indoor temperature range can be expanded; 3) testing human subjects to quantify their comfort and satisfaction under long-term and short-term transient exposures; and 4) preparing a report for designers, owners, and manufacturers of interiors and furniture systems.

*Proposed funding level: $150,000*

**Using feedback from commercial buildings to support energy-conserving behavior at work and at home**

Problem: In 2006, energy use in California's residential buildings resulted in 34 million metric tons (MMT) of greenhouse gas emissions, while energy use in commercial buildings resulted in 14 MMT of GHG emissions. Occupant behavior is an important determinant of energy use, but little information is available to help the State leverage

occupant behavior for GHG reductions in the commercial realm. This research will look at a single method involving feedback to reduce both residential and commercial GHG emissions.
Objective: The project will foster reduced energy consumption in the building sector by: 1) identifying the kinds of energy conservation-related information most likely to influence different segments of the workforce; 2) quantifying the degree to which this information affects energy-conserving beliefs and behaviors at work and at home; and 3) quantifying the GHG reduction potential associated with the stated behaviors. Deliverables include a tool to support reduced energy use and GHG emissions mitigation in the commercial building sector.
*Proposed funding level: $185,000*

*Voluntary Emissions Reductions*

**Reducing energy use through optimized communication of real-time residential energy usage information**

Problem: Although recent studies estimate that behavioral changes can reduce residential energy consumption in California by between 22 and 30 percent over the next 5 to 8 years, it remains unclear how consumers respond to different presentations of information intended to prompt them to voluntarily reduce their electricity consumption. Most previous studies involve small samples of homes in Europe; some studies have even shown that providing consumers with more information results in an increase in electricity usage.
Objective: This project will investigate how to encourage energy conservation through strategic presentation of electricity usage information to residential consumers. Several interventions based on increased feedback (information) to customers will be investigated to explore the roles of private and public information, social norms, social status effects, and existing preconceptions about electricity usage. This research is particularly timely, as a number of California's utilities are installing Smart Grid systems with possible real time consumer feedback.
*Proposed funding level: $330,000*

**Monitoring and evaluating behavioral change strategies that incorporate the CoolCalifornia.org resource developed by ARB**

Problem: Social psychologists suggest that information alone does not suffice to prompt behavioral change. Rather, it is critical to tailor messages to appeal to the values, habits, abilities, worldviews, and social and economic constraints of target audiences; and to leverage social motivations for behavioral change. For example, encouraging individuals to make public commitments, fostering group identification and developing competitions have all been shown to be effective strategies to enable behavioral change.
Objective: This investigation will provide the State with empirical evidence from a California-based study to help identify ways to encourage the public to adopt climate-friendly behaviors. Specifically, this work will: 1) assess total greenhouse gas emissions reduced via the CoolCalifornia and CoolClimate projects; 2) illuminate how new information tools can be most effectively used by the State to encourage more sustainable behavior; and 3) compare the behavioral changes induced by different community-based greenhouse gas reduction programs in California.
*Proposed funding level: $300,000*

## *Economic Analysis*

**Direction of Proposed Research**

Economic impact assessments of air pollution control on California business enterprises and individuals are a key component of ARB's decision-making process, which seeks cost-effective regulatory and non-regulatory measures to attain its goals and protect public health. A number of modeling tools have been developed for economic analysis on statewide climate change and air pollution control policies. Continued evolution of economic modeling and assessment tools will help illuminate bottom-line costs associated with the abatement of air pollution, the ability of small and large firms to pay those costs as well as any penalties that might be involved in noncompliance, and the most cost-effective strategies for simultaneously achieving environmental goals and protecting California's economy.

During FY 2010-2011, ARB will invite an economics fellow to help advance the State's capacity to model impacts of air quality regulations on California's economy and welfare. In collaboration with expert economics modelers and economists familiar with California's regulatory landscape, the fellow will delineate critical research gaps and priorities that need to be addressed to advance our ability to forecast near- and long-term impacts of environmental regulatory and non-regulatory strategies on California's economy. Based on the outcome of this collaboration, ARB will solicit research proposals to address the most critical research gaps.

*Research funding allocation: $480,000*

**Policy Drivers**

- California's Global Warming Solutions Act of 2006 (AB 32)
- AB 32 Scoping Plan
- Early Action regulatory measures
- EO S-3-05 establishing GHG reduction targets for 2020 and 2050
- Diesel Risk Reduction Plan
- Toxic and criteria pollutant reductions

**Research Themes**

- *Forecasting Models*. Evaluate economic forecasting models and methods that can help establish business-as-usual future baselines and corresponding GHG, toxic, and criteria pollutant emission levels.
- *Macroeconomic Impacts*. Identify and characterize macroeconomic impacts on multiple industries and sectors within California.
- *Assessment of Long-term Economic Impacts*. Assist in evaluating GHG economic impacts in California using new modeling techniques beyond the 2020 timeframe.

## *Technology Research and Development*

**Context**

ARB's technology-forcing regulations, particularly those related to tailpipe and crankcase emissions from motor vehicles, have resulted in innovative technology development, and ARB continues to fund research to investigate and promote the understanding, advancement, development, and improvement of technology-based solutions for achieving zero or near-zero emissions from all manmade sources of air pollution in California. ARB also supports research to improve air pollutant and/or greenhouse gas monitoring and emission measurements. These research activities are designed to support regulatory strategies that reduce source-specific emissions as a means of mitigating exposures to air pollution, particularly among sensitive groups or communities that may bear a disproportionate share of air pollution exposure.

**Policy Drivers**

- Mobile source control
- Mobile source emissions monitoring

**Research Themes**

- *Small Off-Road Engines:* Development and dissemination of zero-emission small (less than 25 hp) off-road equipment will help the State reduce emissions from such applications as landscape maintenance, which accounts for significant criteria pollutant as well as GHG emissions.
- *Improved Monitoring Tools*: Enhance ARB's ability to cost-effectively monitor ambient concentrations of and exposures to health-damaging air pollutants.

**Recommended for Funding**

*Small Off-Road Engines*

**Zero on-site pollution for portable power applications including generators and lawnmowers**

Problem: The vast majority of California's professional landscapers use exclusively gasoline fueled lawnmowers, which are a significant source of pollution and exposures. Even the most advanced battery technology is not capable of providing a reasonable solution for professional landscape crews and the bulk of small gasoline engine users. Small gasoline engines are a strong contender for early fuel cell adoption as they are highly polluting, have poor energy efficiency, and may potentially be serviced with existing distribution channels.

Objective: The proposed research will research the necessary components and control systems to support a sodium silicide fueled lawnmower. A prototype will be developed to look and feel like a professional product, suitable to serve as the template for larger-scale production. Research will focus on successful reaction control, thermal management, and fuel cell systems integration.

*Proposed funding level: $376,000*

## Recommended if Additional Funds Available

*Improved Monitoring Tools*

**An improved particle concentrator for inhalation studies**

Problem: Numerous epidemiological studies associate high particle concentration with a range of pulmonary, cardiovascular and systemic health effects, yet toxicological support for these findings requires further animal studies. Exposing laboratory animals to concentrated ambient particles to elicit health effects requires a particle concentrator, but currently available concentrators are insufficiently steady with time and overly sensitive to ambient temperature, relative humidity, and particle concentration.

Objective: The objective is to develop a particle concentrator that, in terms of its concentration factor, is nearly insensitive to ambient conditions and can operate for long periods of time with minimal or no attendance. This reliable, stable particle concentrator will enable improved particle toxicity studies to support establishment of PM standards.

*Proposed funding level: $150,000*

## APPENDIX A: Concepts Recommended for Health Effects and Exposure

### Table of Contents

**TITLE: Season- and location-specific systemic health effects of ambient particulate matter**

**PROBLEM:** A diverse and increasingly sophisticated body of epidemiologic evidence associates environmental particulate matter (PM) with both asthma and cardiovascular morbidity and mortality in exposed populations. Most studies focus on the source of urban particles rather than regional differences in particle composition and their potential pulmonary or systemic health effects. Plausible biologic associations between PM exposure and systemic cardiovascular effects remain unclear. An ongoing problem for regulatory agencies is determining what source or component(s) of particulate matter is responsible for health effects. California's San Joaquin Valley is a unique geographic location with high particulate matter burdens that combine both urban, traffic corridor, and agricultural sources. While regulatory action levels for PM are currently based on mass concentrations, there is interest at both the State and federal level regarding the relative toxicity of PM from different sources. The information obtained from this project should help elucidate the relative contribution of particles of different composition in the health effects associated with PM exposure.

**PREVIOUS WORK:** Ongoing ARB funded work by the investigators demonstrates that platelet activation is a sensitive marker in mice exposed to concentrated ambient PM in the San Joaquin Valley. They found a seasonal effect on systemic cytokines, as winter rural Concentrated Ambient Air Particular Matter (CAPs) exposures result in significantly greater systemic pro-inflammatory responses. Laser capture mRNA analysis of pulmonary airways, blood vessels, and parenchyma demonstrates that there are no changes in expression in any of those tissues in summer urban CAPs exposures, yet winter urban CAPs exposures show clear patterns of mRNA upregulation, indicative of a general increase in xenobiotic metabolism as well as a pro-inflammatory and pro-coagulant response. These data, in combination with in vitro laboratory studies suggest that PM inhalation activates monocytes and platelets in the pulmonary microvasculature, laying the foundation for a systemic cardiovascular response. Theories advanced to explain the mechanism of particle-induced disease emphasize ROS generation catalyzed by transition metals, yet research by these investigators and others suggests that bacterial derived endotoxin may also drive inflammatory responses. The investigators' in vitro data shows that selective portions of these responses can be abrogated by endotoxin binding, antioxidant supplementation, metal chelation, or inhibition of the PAH induced Aryl Hydrocarbon Response Element (ARE). Responses differ based on location; rural site responses appear more endotoxin driven while urban responses are uniquely inhibited by pretreatment with transition metal chelators. Finally, they have demonstrated that intratracheal instillation of collected ambient particles to mice results in a systemic platelet activation response similar to that characterized in field exposures.

**OBJECTIVE:** The following hypothesis will be tested: Regional and seasonal differences in composition of environmental particulate matter from the San Joaquin Valley influence the nature and extent of systemic pro-inflammatory and pro-coagulant responses.

Specific Aim 1: Compare the influence of location-specific ambient particle composition on pro-inflammatory cytokine secretion patterns and platelet activation in mice given intratracheal instillations of collected particles.
Specific Aim 2: Determine the relative contributions of transition metal related ROS generation, PAH compounds and endotoxin on the generation of systemic pro-coagulant and inflammatory responses in mice given intra-tracheal instillations of collected particles.

**DISCUSSION:** The investigators propose to compare in vivo responses of mice to site and season specific samples in context of their elemental and organic chemical analysis. They will use intra-tracheal instillations of PM to compare airway, pulmonary vascular and alveolar expression of genes associated with endothelial, platelet and monocyte activation, expression of proinflammatory cytokines and pro-coagulant molecules in the systemic circulation and systemic platelet activation.
Approach: Each experiment will compare 6 mice given intratracheal instillations of collected ambient PM at a total dose equal to the calculated cumulative dose in a representative 2 week CAPs exposure. Previous studies have shown that groups of 6 mice are sufficient to detect significant differences between group responses. Control mice receive saline extracts from clean collection filters. Endpoints to be evaluated are 1) gene expression of Reactive Organic Species (ROS), PAH and inflammatory response elements in airways, vessels and parenchyma, 2) Expression of a panel of 36 inflammatory mediators in the lung and plasma, and 3) Markers of platelet activation including the presence of microaggregates, microvesicle formation, alterations in integrin expression, and secretion of alpha and lysosomal granule components. Plasma fibrininogen levels, an acute phase protein and pro-coagulant protein will also be determined.

From the results of studies comparing summer and winter PM collected from urban and rural Fresno, the investigators propose to select two samples, based on the most divergent composition and inflammatory responses, to evaluate the relative contribution of particle components to systemic responses. They will pre-incubate PM with the endotoxin binding antibiotic polymixin B or the metal chelator desferoxamine maleate to determine the relative biologic importance of each in induction of inflammatory responses. To evaluate the relative importance of PAH components, they will compare responses to whole PM with responses to PM previously extracted with hexane.

Results of animal studies will be correlated with summary compositional analysis data. They will use a multiple regression approach to develop correlation coefficients for the percentage change in each biologic endpoint with the percentage of elemental carbon, percentage of organic carbon, mass concentration of transition metals and mass concentration of PAH in samples from each source.

**BENEFITS:** Regulation of environmental PM is currently based on size and mass. Stronger support for source-apportioned regulation depends on correlating source specific composition with health effects. While not directly apportioning composition to sources, this project will correlate composition, season, and location with biologic markers relevant to cardiovascular disease. Results will provide a biological link between epidemiologic studies and a principal health outcome of PM exposure. It is

entirely possible that rural source PM acts through different mechanisms than PM from urban sources. If true, this would have great significance for regulatory and health monitoring activities.

**CO-FUNDING:** This project would be a logical extension of the investigators' currently funded work. It is only possible because they have a well-characterized collection of season and location specific ambient particles from the San Joaquin Valley (in collaboration with the Kleeman Lab) and have previously established that their results with intra-tracheal instillations recapitulate those with CAPs exposures. This project will complement human exposure and CAPs exposures proposed in the SAHRC EPA program renewal.

**COST:** $266,298

**REFERENCES:**


Alexis, N. E., Lay, J. C., Zeman, K., Bennett, W. E., Peden, D. B., Soukup, J. M., Devlin, R. B., and Becker, S. (2006). Biological material on inhaled coarse fraction particulate matter activates airway phagocytes in vivo in healthy volunteers. *J Allergy Clin Immunol* 117, 1396-1403.

Becker, S., Dailey, L. A., Soukup, J. M., Grambow, S. C., Devlin, R. B., and Huang, Y. C. (2005). Seasonal variations in air pollution particle-induced inflammatory mediator release and oxidative stress. *Environ Health Perspect* 113, 1032-1038.

Nel, A. (2005). Atmosphere. Air pollution-related illness: effects of particles. *Science* 308, 804-806.

Vidrio, E., Phuah, C. H., Dillner, A. M., and Anastasio, C. (2009). Generation of hydroxyl radicals from ambient fine particles in a surrogate lung fluid solution. *Environ Sci Technol* 43, 922-927.

Wilson, D. W., Aung, H. H., Lame, M. W., Plummer, L., Pinkerton, K. E., Ham, W., Kleeman, M., Norris, J. W., and Tablin, F. (2010) Exposure of mice to concentrated ambient particulate matter results in platelet and systemic cytokine activation. *Inhal Toxicol* 22, 267-276.

Xia, T., Kovochich, M., and Nel, A. (2006). The role of reactive oxygen species and oxidative stress in mediating particulate matter injury. *Clin Occup Environ Med* 5, 817-836.

**TITLE: Biological activity associated with near-freeway particles and gases**

**PROBLEM:** Epidemiological studies have shown associations between residential exposure to near roadway air pollutants and mortality and exacerbation of diseases, including wheeze and asthma, reduced lung function, and chronic obstructive pulmonary disease. A large number of in vitro and animal studies have shown that diesel and ambient particulate matter have pro-oxidant activity relevant to the pathogenesis of these conditions. In addition, the pattern of near roadway exposures to ultrafine particulate matter and other traffic-related pollutants has been shown to correspond to the near-roadway residential distance gradient in the prevalence of asthma in southern California.[1-4] It is therefore surprising that there has been no previous study examining biologically-relevant activity associated with long-term collections of ambient air at multiple locations in the impact zone downwind of major roadways. Such roadway gradient studies would provide an opportunity to elucidate the biologic mechanisms causing the health effects and to identify the components of ambient traffic-related pollution potentially responsible for these effects.

The investigators propose to examine the spatial gradient in the biological activity of chronic exposure to particle and vapor phase pollutants relevant to asthma pathogenesis upwind and downwind from a major truck and automobile corridor in Los Angeles, and to correlate these findings to relevant composition of the aerosol. Pro-oxidant, electrophilic, inflammatory, and allergic properties of particles and/or vapors will be measured in vitro, using standard and novel assays. In addition, they will examine adaptive (protective) cellular responses. Relevant size-distributed chemical composition and vapors will also be measured.

**PREVIOUS WORK:** The University of Southern California (USC) and the University of California, Los Angeles (UCLA) investigators have recently adapted instrumentation to collect size-resolved PM (coarse, fine, quasi-ultrafine) at low flow rates to allow multiple 2-week integrated samples that can be composited to estimate seasonal average exposures. They have also adapted standard assays for measuring pro-oxidant, inflammatory, electrophilic and allergic properties in these particles. In addition, they have developed assays to evaluate a common susceptibility (present in 40 percent of the population) associated with knocking down the protective enzyme GSTM1 using small inhibitory RNA.

In previous studies of Los Angeles Basin air samples, the investigators demonstrated that vapor-phase pollutants are responsible for most of the electrophilic activity (which inactivated proteins by forming irreversible covalent bonds) while the particle phase that exhibits far greater redox activity.[5] Therefore, both gas and particle phase pollutants need to be collected to evaluate the full complement of health impacts of air pollution. Furthermore, electrophiles in the vapors have been shown to activate the Nrf2-based antioxidant response element to increase expression of protective downstream proteins.[6] Concurrently, an inflammatory response, mediated by the MAP kinase pathway, occurs at comparable exposure concentrations. Thus, the investigators' results show that both vapor and particulate phase pollutants play important roles in the health effects of air pollutants and that protective effects at ambient levels may be offsetting some or sometimes all of the inflammatory and oxidative stress reactions.

Therefore, the ratio of adaptive-to-inflammatory responses to a given concentration of pollutants may determine the extent of adverse health effects.

**OBJECTIVE:** The study's objective is to evaluate the seasonal and spatial variation in pollutants and in ambient air biological activity upwind and at 5 locations downwind from the I-5 freeway. Investigators will examine the distance decay in PM0.2, PM2.5 and PM10-2.5 mass and composition, including model pro-oxidant and electrophilic species, which they expect will vary in the vapor and particle phase and by particle size and composition. They also will examine the role of chemical composition in determining the pro-oxidant, electrophilic, allergic, and inflammatory activity of ambient aerosols. Spatial variation in the protective antioxidant responses is unknown, but they hypothesize that vapor electrophilic activity will induce greater protective antioxidant response. They also hypothesize that reduction in cellular GSTM1 activity will result in greater oxidative stress.

**DISCUSSION:** PM will be collected at logarithmically-spaced distances downwind from the freeway for two, two-week periods (a total of four weeks in the summer and four in the winter) and will be composited by season. PM mass in each size fraction will be determined gravimetrically. Metals, elemental carbon and organic carbon (as described above) in each PM size cut will be measured using standard methods.

The concentration of pro-oxidants and electrophiles in each sample will be determined by the dithiothreitol (DTT)-based redox assay and the glyceraldehyde-3-phosphate dehydrogenase (GAPDH) assay, respectively. The actions of the samples on the inflammatory and adaptive transcription factors will be determined in a mouse macrophage cell line (Raw 246.7) using immunoblot procedures to estimate levels of AP-1, NFkappaB and Nrf2 following exposure.

Pro-inflammatory effects will be assessed by measuring cytokine response (IL-8 ;GM-CSF;IL-1β) and phase II enzyme expression (GSTM1, GSTP1, HO-1 and NQO1) in primary human airway epithelial cells that are GSTM1 positive. These assays will be repeated after inhibiting GSTM1 with siRNA. TNFα; IL-6; MIP-2; and nitric oxide response will be measured in mouse alveolar macrophage cell line MH-S, because it is not possible to obtain sufficient cells from humans. Allergic effects will be assessed by measurement of IgE release in human peripheral blood mononuclear cells and of hexosaminidase in the rat basophil cell line RBL-SX38.

Correlations of freeway distance, particle and vapor composition with various biological activity indicators will be examined. Metals will be grouped based on their source specificity, e.g., Cu, Sb in coarse and fine particulate suggestive of brake wear. The relationship of pro-oxidant and electrophilic species with inflammatory and allergic responses and with assays of oxidative stress will be examined. The relationship of electrophilic species to adaptive response and the modulating effect of these responses on harmful responses will also be assessed.

**BENEFITS:** This project is an opportunity to develop and test a new approach for studying near roadway air pollution effects, to examine mechanisms of the health effects of traffic emissions, and to identify the components of traffic-related pollutants

potentially responsible for these effects. Demonstrable gradients that the investigators hypothesize will exist would provide strong biological plausibility to the epidemiological findings and reduce the uncertainty both in the causal relationship and in the spatial pattern of risk. Together, these findings could provide important information to guide the development of better regulatory and public health policy. Scientific uncertainty to the causal relationship expressed in a recent influential review of the literature[7] is a limitation to development of policy, such as the California requirement that schools be located 500 feet from freeways. Greater precision of the gradient of biological effects would help develop more precise buffers. These methods also offer possible alternative approaches to exposure assessment in population studies of chronic health effects of air pollution.

**CO-FUNDING:** USC and UCLA own all equipment necessary to perform this study. Co-funding with the SCAQMD and NIH will be pursued.

**COST:** $300,000 (*original concept requested $453,000*)

**REFERENCES:**


1. Salam MT, Islam T, Gilliland FD. Recent evidence for adverse effects of residential proximity to traffic sources on asthma. *Curr Opin Pulm Med* 2008 Jan; 14(1):3-8.
2. Zhu Y, Hinds WC, Kim S, Sioutas C. Concentration and size distribution of ultrafine particles near a major highway. *J Air Waste Manag Assoc* 2002 Sep; 52(9):1032-42.
3. Salam MT, Lin PC, Avol EL, Gauderman WJ, Gilliland FD. Microsomal epoxide hydrolase, glutathione S-transferase P1, traffic and childhood asthma. *Thorax* 2007 Dec;62(12):1050-7.
4. McConnell R, Berhane K, Yao L, Jerrett M, Lurmann F, Gilliland F, et al. Traffic, susceptibility, and childhood asthma. *Environ Health Perspect* 2006 May;114(5):766-72.
5. Eiguren-Fernandez A, Shinyashiki M, Schmitz D, DiStefano E, Hinds W, Kumagai Y, Cho A and Froines J Redox and electrophilic properties of vapor- and particle-phase components of ambient aerosols. *Environmental Research* 2010 in press.
6. Shinyashiki M, Eiguren-Fernandez A, Schmitz DA, Di Stefano E, Li N, Linak WP, Cho SH, Froines JR and Cho AK Electrophilic and redox properties of diesel exhaust particles. *Environ Res* 2009;109:239-244.
7. Health Effects Institute (2010). "Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects." Special Report 17. Jan. 12, 2010. Available at: http://pubs.healtheffects.org/view.php?id=334

**TITLE: Risk of pediatric asthma morbidity from multipollutant exposures**

**PROBLEM:** Asthma morbidity (including hospital admissions) has been associated with daily concentrations of ambient air pollution (PM2.5 and Ozone in particular)[1] and with traffic-related air pollutants near the home.[2] However, there is a lack of data on the importance of local exposure to traffic-related ultrafine particles (UFP, <0.1 μm) and its relationship to regional exposure to PM2.5 and Ozone organic components. In particular, little is known about the health effects of two important classes of particles in California, namely:

1) Primary organic aerosols (POA) directly emitted from combustion sources; and
2) Secondary organic aerosols (SOA), which are largely photochemically-produced.

These particle types have different spatial and temporal variability and they are thus minimally correlated in California.[3,4] The organic component mix and size distribution differs as well, with POA being the predominant mass fraction in near-roadway UFP and SOA comprising a large part of accumulation mode particles (0.1-2.5 μm). Furthermore, POA components are more hydrophobic, and SOA components are more hydrophilic. These characteristics will likely determine their toxicity and differential effects in the airways. Furthermore, unregulated UFP may be more toxic than other size fractions because of number concentrations and surface area are magnitudes higher than larger particles, which dominate PM mass. Finally, studies reporting associations of ambient PM2.5 mass with asthma outcomes have been important to the regulatory protection of susceptible populations of children, but effect magnitudes may have been underestimated or obscured since a large fraction of the PM mass is biologically inactive while a variable and often small fraction has the potential to induce oxidative stress and inflammation.[5]

**PREVIOUS WORK:** Dr. Delfino and colleagues recently reported positive associations of recurrent episodes of asthma requiring hospital care with chronic exposure to traffic-related air pollution exposures ($NO_X$ and CO) near 2,768 subject residences in Orange County.[2] Exposures were estimated with CALINE4 dispersion models. Associations were stronger for females and infants but not significantly. The investigators concluded that traffic-related air pollution adversely affects asthma severity.

The proposed study greatly advances this previous research by: 1) assessing acute exposure-response relationships for each hospital encounter; 2) adding estimated residential exposure to POA, SOA and UFP; and 3) nearly tripling the sample size. The proposed study will leverage co-funded efforts to predict size-resolved PM exposures with high temporal-spatial resolution, and to establish a dataset of subjects with addresses linked to all asthma hospital encounters (>10,000 emergency department visits and hospital admissions).

In another study,[6] Dr. Delfino and colleagues followed 60 elderly subjects with weekly repeated measures of airway inflammation estimated from the fractional concentration of nitric oxide (NO) in exhaled air. Particulate air pollutants were measured daily in the outdoor home environment of the subjects' retirement communities. The investigators collected PM<0.25 μm (PM0.25), made aqueous extracts of the PM0.25 filters, and assayed extracts for chemical tracers of POA and SOA. They also estimated primary

and secondary organic carbon fractions of PM2.5.[7] Exhaled NO was positively associated with SOA markers and Ozone but not with POA markers. Data in a larger sample of subjects with asthma (proposed here) are needed to fully address the relative importance of POA and SOA to respiratory health.

**OBJECTIVE:** The investigators will use PM predictions generated by regional air quality models (Michael Kleeman, UC Davis) to study the relation of asthma morbidity in over 7,500 children to exposure to POA and SOA. They will evaluate whether variations in this important characteristic of PM2.5 affects the relation of PM2.5 mass concentrations to asthma morbidity (emergency department visits and hospital admissions). The investigators hypothesize that traffic-related number concentrations of UFP near subject homes and related estimates of exposure to POA will show associations with asthma morbidity that are additive with estimates of exposure to SOA and Ozone. This addresses the multipollutant nature of human exposure, which includes both ambient and microenvironmental particle and gas components. Finally, they will evaluate air pollution susceptibility, including asthma recurrence and socioeconomic status.

**DISCUSSION:**

Task 1. *Estimate exposures for children with asthma to primary and secondary organic aerosols*.

The UCD/CIT Source-Oriented Chemical Transport Model (Kleeman) will be modified to output daily POA and SOA at 5x5 km resolution from 2000-2008 for 7,500 children in North Orange County. The POA and SOA model output will include size-resolved mass, speciation, and source apportionment. SOA and POA model estimations will be validated using particle composition data from the study of 60 elderly subjects (discussed above).

Task 2. *Assess the risk of emergency department visits and hospital admissions for asthma in children from exposure to both traffic-related particles near their homes and local ambient primary and secondary organic aerosols and Ozone*.

The new POA-SOA exposure data from Task 1 will be combined with traffic-related air pollutant exposures (ultrafine PM, PM2.5, $NO_2$, $NO_x$, and CO) and Ozone near geocoded subject residences that will have been estimated under separate funding.

Task 3. *Stratify subjects based on recurrence of hospital encounters in order to assess whether children with multiple encounters show the strongest associations with air pollutants.*

Task 4. *Assess effect modification of associations by subject demographic and socioeconomic characteristics*.

The study will evaluate associations using a case-crossover design and conditional logistic regression.[8] Each person acts as their own control. The investigators will test regression estimates for lag 0-6 exposure days, and weekly cumulative averages.

The strength of this design is that it generates a complete PM dataset (resolved by space, time, speciation, and source apportionment), it involves individual-level data rather than aggregate administrative data normally employed in time series studies, and

it enables assessments of the risk of hospital utilization from both spatial and temporal differences in air pollutant exposures, which has only once been evaluated in a case-crossover study of asthma and air pollution (in France).[9]

**BENEFITS:** Because asthma requiring medical care at a hospital represents a diagnosed severe exacerbation of asthma, the findings of this study will have implications regarding important clinical and economic impacts of air pollution. Subjects will also be stratified based on recurrence of hospital encounters to asses whether the most severely affected children show the strongest associations with air pollutants. In addition, one of the most pervasive determinants of air pollution exposure by children living in California is residence near freeways and major surface streets. Children in low income communities may be more likely to live near high density traffic.[10] Therefore, results regarding differences between socioeconomic groups in this study are of particular importance.

Finally, findings using $PM_{2.5}$ organic fractions and UFP could have importance to the Federal and State regulation of particles based on total $PM_{2.5}$ mass concentration. This is because the mass fraction of toxic components with oxidative or pro-inflammatory potential may be small and highly variable. Of particular benefit is the ability of this study to compare modeled air pollutant exposures that are spatially variable at the residential level (UFP and POA) to estimates of exposures such as SOA and $O_3$ representing more homogenous background air pollutants.

**COST:** $285,000

**REFERENCES:**


1. Kim JJ; American Academy of Pediatrics Committee on Environmental Health. Ambient air pollution: health hazards to children. *Pediatrics* 2004;114:1699-1707.
2. Delfino RJ, et al. Repeated hospital encounters for asthma in children and exposure to traffic-related air pollution near the home. *Ann Allergy Asthma Immunol*, 2009a;102:138-144.
3. Delfino RJ et al. Association of biomarkers of systemic effects with organic components and source tracers in quasi-ultrafine particles. *Environ Health Perspect*, in press.
4. Delfino RJ, Staimer N, Tjoa T, Gillen D, Polidori A, Arhami M, Kleinman MT, Vaziri N, Longhurst J, Sioutas C. Air pollution exposures and circulating biomarkers of effect in a susceptible population: clues to potential causal component mixtures and mechanisms. *Environ Health Perspect*, 2009b;117:1232–1238.
5. Ayres JG et al. Evaluating the toxicity of airborne particulate matter and nanoparticles by measuring oxidative stress potential--a workshop report and consensus statement. *Inhal Toxicol* 2008;20(1):75-99.
6. Delfino RJ, et al. Airway and systemic inflammation are differently associated with primary and secondary organic aerosols in an elderly panel cohort. *Epidemiol*, submitted.
7. Polidori et al. Indoor-outdoor relationships, trends and carbonaceous content of fine particulate matter in retirement communities of the Los Angeles basin. *J Air Waste Manage Assoc*, 2007;57:366-379.
8. Lumley T, Levy D. Bias in the case-cross over design: implications for studies of air pollution. *Environmetrics* 2000;11:689-704.
9. Laurent O, Pedrono G, Segala C, Filleul L, Havard S, Deguen S, Schillinger C, Rivière E, Bard D. Air pollution, asthma attacks, and socioeconomic deprivation: a small-area case-crossover study. *Am J Epidemiol* 2008;168:58-65.
10. Gunier RB, Hertz A, Von Behren J, Reynolds P. Traffic density in California: socioeconomic and ethnic differences among potentially exposed children. *J Expo Anal Environ Epidemiol* 2003;13:240-6.

**TITLE: Investigation of persistent immune effects of acute PM exposure during early life and development of a biomarker for lung function decline**

**PROBLEM:** Epidemiologic studies support a link between air pollutant exposures during early life and development of lung function decrements.[1-4] Although these findings provide important correlative data in human subjects, the biologic mechanisms for these effects are not understood. Evaluation of children is restricted due to limitations in experimental assessment and methodology. As with adults, it is clear that inflammation is a consistent effect of air pollutant exposure in children.[5] Yet, early life exposures in children are distinguished by the establishment of a persistent effect on lung function that is retained at maturity. It has been speculated that the contemporaneous maturation of lung and immune systems during infancy provides a critical window of susceptibility for epigenetic changes.

Immunological markers of environmental challenge have been evaluated in children (reviewed in Duramad et al[6]), but there are few valid biomarkers for air pollution exposure. There is currently no data available on the impact of air pollutant exposures on the functional status of immunity in infants and school-age children. Importantly, there are no early life biomarkers (immune or otherwise) that are predictive of lung function decrements at maturity. To address this problem, the investigators propose to study the impact of air pollutant exposure on immune and lung function by evaluating a cohort of rhesus monkeys that were born and raised in an outdoor environment at the California National Primate Research Center during the spring of 2008, just prior to significant PM exposure from the Trinity and Humboldt County wildfires in July 2008.

**PREVIOUS WORK:** To determine if early life exposure to air pollution has a persistent effect on the immune system, the investigators, affiliated with the University of California, Davis (UCD), have recently completed studies using the rhesus monkey as an animal model of childhood development. They hypothesized that the functional status of the immune system could be measured by challenge with ligands for toll-like receptors. In brief, toll-like receptors are a family of ten (TLR1-10) constitutively expressed immune receptors that serve as critical mediators of inflammation in response to a variety of pathogens. To test this hypothesis, monkeys were exposed to cyclic ozone (1 cycle = 9 days filtered air + 5 days 8 hrs/d 0.5 ppm ozone) starting at 30 days of age for 5 cycles or 11 cycles, followed by filtered air housing. At one year of age, immune function status was evaluated by (a) in vivo challenge with lipopolysaccharide, a TLR4 ligand and (b) in vitro challenge of peripheral blood cells with lipopolysaccharide, poly I:C, or flagellin, which are ligands for TLR4, TLR3, and TLR5, respectively. Following inhalation of lipopolysaccharide, animals that had a history of ozone exposure generated a reduced airways inflammatory response relative to control animals. Similarly, peripheral blood from ozone-exposed animals exhibited a reduced response to toll-like receptor ligand stimulation. These data show that early life exposure can persistently modulate the immune system, such that the immediate response to pathogens is attenuated. This proposal will expand on this previous work by investigating ambient exposure with an emphasis on peripheral blood analysis and lung function measurements.

**OBJECTIVE:** The objective of this proposal is to assess the early life impact of wildfire PM exposure on immune and lung function parameters, and to develop an immune biomarker of lung function decline. To complete this objective, the investigators will evaluate a cohort of rhesus monkeys that were born in an outdoor environment within three months prior to the summer wildfires of July 2008 in northern California. The rationale for this approach is that the immune system and lung architecture of the rhesus monkey is most similar to that of humans, as compared with other animal models. As such, these animals serve as excellent biological sentinels for the health effects of Sacramento and Yolo county air pollution. Importantly, this approach can be translated into larger human population studies to determine the impact of this exposure in school-age children.

**DISCUSSION**: In the research proposed here, the investigators will evaluate a cohort of rhesus monkeys that were born within three months prior to the July 2008 Trinity and Humboldt County fires (n=40). Because these animals were housed in an outdoor colony, they were also exposed to ambient ozone. As such, the study will also evaluate age-matched monkeys were born in the outdoor colony in the subsequent year (2009), as a control group (n=40). The investigators will collect peripheral blood samples from animals and culture with the following toll-like receptor ligands in a dose dependent fashion:

1. Lipopolysaccharide (LPS)-a cell wall component of gram negative bacteria
2. Poly I:C - a mimic for RNA viruses (i.e. respiratory syncitial virus)
3. Flagellin- a component of flagellated bacteria (i.e. Pseudomonas)

Output parameters for these cultures is measurement of interleukin-8 and interleukin-6 protein secretion by standard ELISA methods. If the functional status of the immune system is affected by PM 2.5 exposure, it is expected that animals born in 2008 will have a significant reduction in the ability to respond to toll-like receptor ligand stimulation, relative to animals born in 2009. Because an ARB air sampling site is located within two miles of the California Primate Research Center that houses the cohort of rhesus monkeys, the investigators will also be able to correlate exposure level with immune response.

In addition to measurement of peripheral blood immune responses, the investigators will also complete lung function measures for each animal enrolled in the study. Physiologic measures will include tidal volume, forced expiratory volume, and airways hyperresponsiveness to a non-specific stimuli (methacholine). If a link exists between immune function and lung function, they would expect to observe a significant correlation between reduced responsiveness to toll-like receptor stimulation and lung function deficits.

Because an important goal of this study to assess a potential biomarker for the human population, it should be emphasized that these studies will not be terminal. Rather, investigators will use physiologic measures and samples that are minimally invasive to

acquire. With additional funding support this offers the opportunity to periodically evaluate this cohort of exposed animals in a longitudinal fashion.

**BENEFITS:** Upon completion of the studies outlined in this proposal, investigators expect that these findings will provide valuable reference data for the health impacts of wildfire PM exposure during early life. Importantly, because of the minimally invasive nature of the study, this approach can be immediately translated into studies designed to investigate identical parameters in human subjects. Although the focus of this proposal is to obtain an immune biomarker for lung function decline, it should be emphasized that this is also indicative of immune system decline that could have important implications with regards to susceptibility to infectious disease.

**CO-FUNDING**: A subgroup of the animals proposed for this study (n=24) are currently enrolled in NHLBI R21HL089148 "Temperament as a Risk Factor in a Monkey Model of Asthma Susceptibility" (John Capitanio, P.I.), which is a minimally-invasive, non-terminal project that will investigate the link between behavior and lung function. The UCD investigators will be able to utilize the lung function data collected from Dr. Capitanio's study in conjunction with evaluation of peripheral blood samples, thereby providing a substantial savings in time and resources.

**COST:** $268,141

**REFERENCES:**


1. Frischer T, Studnicka M, Gartner C, Tauber E, Horak F, Veiter A, Spengler J, Kuhr J, Urbanek R, Lung function growth and ambient ozone: a three-year population study in school children. *Am J Respir Crit Care Med* 1999;160: 390-396.
2. Boezen HM, van der Zee SC, Postma DS, Vonk JM, Gerritsen J, Hoek G, Brunekreef B, Rijcken B, Schouten JP, Effects of ambient air pollution on upper and lower respiratory symptoms and peak expiratory flow in children. *Lancet* 1999;353: 874-878.
3. Horak F, Jr., Studnicka M, Gartner C, Spengler JD, Tauber E, Urbanek R, Veiter A, Frischer T, Particulate matter and lung function growth in children: a 3-yr follow-up study in Austrian schoolchildren. *Eur Respir J* 2002;19: 838-845.
4. Gauderman WJ, Avol E, Gilliland F, Vora H, Thomas D, Berhane K, McConnell R, Kuenzli N, Lurmann F, Rappaport E, Margolis H, Bates D, Peters J, The effect of air pollution on lung development from 10 to 18 years of age. *N Engl J Med* 2004;351: 1057-1067.
5. Frischer T, Kuehr J, Pullwitt A, Meinert R, Forster J, Studnicka M, Koren H, Ambient ozone causes upper airways inflammation in children. *Am Rev Respir Dis* 1993;148: 961-964.
6. Duramad P, Tager IB, Holland NT, Cytokines and other immunological biomarkers in children's environmental health studies. *Toxicol Lett* 2007;172: 48-59.

**TITLE: Evaluation of secondary pollutant emissions from portable "air cleaners"**

**PROBLEM:** In a recent survey, 14 percent of California households reported ownership or use of portable air cleaner during the past five years[1]. A majority of portable air cleaners are electrostatic precipitators (ESPs), ionizers and ozone generators (OGs), all of which may negatively impact indoor air quality (IAQ) through emissions of ozone ($O_3$).[2,3] Hence, nearly one million Californians may be exposed to potentially harmful pollutants emitted by poorly engineered air cleaning devices. Increasing public awareness of the deleterious effects of indoor ozone is likely driving consumers to seek alternative products available in a dynamic multi-million dollar market. Several new products combine new technology such as $TiO_2$ photocatalytic oxidation with established technologies in an integrated device. While ozone emissions remain a concern, formaldehyde and other partially oxidized VOCs may be generated as undesired byproducts of chemical processes taking place inside the air cleaner unit. These new integrated devices are capturing a growing market share, but research is needed to evaluate potential IAQ and public health impacts of these new generation devices.

**PREVIOUS WORK:** Characterization of ozone emissions by OGs, ESPs and ionizers has been carried out by ARB staff and other investigators[2-4]. Several other studies on portable air cleaners evaluated their effectiveness at removing aerosol particles[5-8], microbes[9] and VOCs[10, 11]. However, little attention has been paid to the generation of secondary organic pollutants formed during the operation of portable air cleaning devices. Recent work investigated the performance of a prototype in-duct whole-building photocatalytic oxidation (PCO) air cleaner through observations and quantification of the formation of volatile aldehydes and carboxylic acids as partial oxidation byproducts upon challenging the device with realistic indoor VOC mixtures,[12,13]. Those results, together with more recent bench-scale studies performed in the principal investigator's laboratory,[14] suggest that PCO air cleaners, when operated under certain conditions and in the absence of secondary treatment, may constitute a significant source of harmful byproducts such as formaldehyde. Similar results have also been described by other authors,[15, 16] further illustrating that the yield of secondary pollutants is highly dependent on experimental conditions, including the composition of the VOC mixture and the concentration of key constituents. In recent ARB-funded projects, the principal investigator's group has characterized secondary pollutants from ozone-initiated indoor chemistry[17, 18] and emissions from office electronic equipment under idle and active cycles,[19] gaining valuable insight on the key physical-chemical phenomena involved and the experimental and analytical tools required to perform the proposed study.

**OBJECTIVE:** The objective of this project is to evaluate the emission of indoor pollutants by devices commercialized as portable air cleaners in California, with emphasis on a new generation of equipment integrating several technologies that include PCO. Emissions will be determined in realistic indoor conditions, to assess the risks associated with exposure to those secondary pollutants.

**DISCUSSION:** Given the large number and diversity of portable air cleaners, ***Task 1*** will involve performing a survey of equipment and technologies available in California

through chain-store retailers and online vendors. This initial screening will allow the investigators to identify devices with a likely significant presence in the state. A representative subset will be selected, in consultation with ARB staff, to perform this study. ***Task 2*** will involve the development of a test protocol for portable air cleaners. Devices will be operated inside a stainless steel, 20-$m^3$ chamber under a controlled atmosphere generated by continuous infusion of a challenge VOC mixture, at air exchanges typical of buildings (in the range 0.2 – 1.5 $h^{-1}$). Key parameters to be optimized include the composition of the chamber atmosphere and concentration of VOCs introduced in the chamber (which will include formaldehyde precursors such as alcohols and terpenes). Also, the study should be applicable to test equipment of different dimensions and different airflow throughput under comparable experimental conditions. ***Task 3*** will comprise the characterization of emissions of secondary pollutants by each of the air cleaners selected during Task 1, following the protocol developed under Task 2 for several air exchange conditions. This third task will be carried out with brand-new units, following manufacturers' operation procedures. In ***Task 4***, the air cleaners will be removed from the chamber and operated continuously in real indoor environments to age the test units. The investigators will also determine emissions in these real-world settings. Subsequently, ***Task 5*** will involve a repetition of the tests performed under Task 3 using the aged equipment, to evaluate possible changes of emissions of secondary pollutants. Finally, in ***Task 6*** the data obtained in Tasks 3-5 will be used to estimate the expected IAQ impact of each of the studied devices using a mass balance model.

**BENEFITS:** Ineffective portable air cleaners may lead to poor IAQ and associated adverse health effects for a significant number of Californians. The proposed research will help the State assist the public in making informed decisions when purchasing and using these devices. Information generated in this work would contribute to the broader effort that the ARB has been carrying out in this field over the past years.

**CO-FUNDING:** Over the past 3 years, the proposing investigators carried out the characterization of whole-building PCO systems in a DOE-funded project. In a related "seed" project, the proposing investigators developed tools to better understand the effects of key parameters in PCO efficacy and byproduct formation, as well as the performance of integrated air cleaner systems. These, together with other smaller PCO projects currently underway, provide synergistic support, experimental infrastructure and methods for the proposed research. This project will provide opportunities for UC students to carry out experimental work as part of their graduate research.

**COST:** $400,000 (*original submission requested ~$350k/year, for 3 years*)

**REFERENCES:**


1. Piazza, T.; Lee, R. H.; Hayes, J. *Survey of the use of ozone-generating air cleaners by the California public.*; Final Report prepared for the California ARB and Cal EPA, Contract 05-301: www.arb.ca.gov/research/apr/past/05-301.pdf, 2006.
2. Phillips, T.; Jakober, C. *Evaluation of ozone emissions from portable indoor "air cleaners" that intentionally generate ozone*; Staff Technical Report to the California ARB: www.arb.ca.gov/research/indoor/o3g-rpt.pdf, 2006.
3. Jakober, C.; Phillips, T. *Evaluation of ozone emissions from portable indoor air cleaners: electrostatic precipitators and ionizers*; Staff Technical Report to the California ARB: www.arb.ca.gov/research/indoor/esp_report.pdf, 2008.

4. Tung, T. C. W.; Niu, J. L.; Burnett, J.; Hung, K. Determination of ozone emission from a domestic air cleaner and decay parameters using environmental chamber tests *Indoor and Built Environ.* 2005, *14*, 29-37.
5. Ward, M.; Siegel, J. A.; Corsi, R. The effectiveness of stand alone air cleaners for shelter-in-place *Indoor Air* 2005, *15*, 127-134.
6. Shaugnessy, R. J.; Levetin, E.; Blocker, J.; Sublette, K. L. Effectiveness of portable indoor air cleaners: sensory testing results *Indoor Air* 1994, *4*, 179-188.
7. Shaugnessy, R. J.; Sextro, R. G. What is an effective portable air cleaning device? A review *J. Occup. Environ. Hyg.* 2006, *3*, 169-181.
8. Macintosh, D. L.; Myatt, T. A.; Ludwig, J. F.; Baker, B. J.; Suh, H. H.; Spengler, J. D. Whole house particle removal and clean air delivery rates for in-duct and portable ventilation systems *J. Air and Waste Manag. Assoc.* 2008, *58*, 1474-1482.
9. Cheng, Y. S.; Lu, J. C.; Chen, T. R. Efficiency of a portable indoor air cleaner in removing pollens and fungal spores *Aerosol Sci. and Technol.* 1998, *29*, 92-101.
10. Howard-Reed, C.; Nabinger, S. J.; Emmerich, S. J. Characterizing gaseous air cleaner performance in the field *Building and Environment* 2008, *43*, 368-377.
11. Howard-Reed, C.; Henzel, V.; Nabinger, S. J.; Persily, A. K. Development of a field test method to evaluate gaseous air clener performance in a multizone building *J. Air and Waste Manag. Assoc.* 2008, *58*, 919-927.
12. Hodgson, A. T.; Destaillats, H.; Sullivan, D.; Fisk, W. J. Performance of ultraviolet photocatalytic oxidation for indoor air cleaning applications *Indoor Air* 2007, *17*, 305-316.
13. Hodgson, A. T.; Destaillats, H.; Hotchi, T.; Fisk, W. J. Evaluation of a Combined Ultraviolet Photocatalytic Oxidation (UVPCO) / Chemisorbent Air Cleaner for Indoor Air Applications *Report prepared to the Building Technologies Program of the U.S. Department of Energy, Contract No. DE-AC02-05CH11231. [LBNL - 62202]* 2007.
14. Quici, N.; Vera, M.L.; Choi, H.; Li Puma, G. ; Dionysiou, D.D. ; Litter, M.I. ; Destaillats, H. Effect of key parameters on the photocatalytic oxidation of toluene at low concentrations in air under 254+185 nm UV irradiation. *Applied Catalysis B: Environmental* 2010, in press. http://dx.doi.org/10.1016/j.apcatb.2010.01.009
15. Ginestet, A.; Pugnet, D.; Rowley, J.; Bull, K.; Yeomans, H. Development of a new photocatalytic oxidation air filter for aircraft cabin *Indoor Air* 2005, *15*, 326-334.
16. Sun, Y.; Fang, L.; Wyon, D. P.; Wisthaler, A.; Lagercrantz, L.; Strom-Tejsen, P. Experimental research on photocatalytic oxidation air purification technology applied to aircraft cabins *Building and Environment* 2008, *43*, 258-268.
17. Nazaroff, W. W.; Coleman, B. K.; Destaillats, H.; Hodgson, A. T.; Liu, D. L.; Lunden, M. M.; Singer, B. C.; Weschler, C. *Indoor air chemistry: cleaning agents, ozone and toxic air contaminants*; Final Report. Contract # 01-336 - California Air Resources Board: http://www.arb.ca.gov/research/abstracts/01-336.htm#Disclaimer, 2006.
18. Destaillats, H.; Lunden, M. M.; Singer, B. C.; Coleman, B. K.; Hodgson, A. T.; Weschler, C. J.; Nazaroff, W. W. Indoor secondary pollutants from household product emissions in the presence of ozone. A bench scale study. *Environ. Sci. Technol.* 2006, 4421-4428.
19. Maddalena, R. L.; McKone, T. E.; Destaillats, H.; Russel, M. L.; Hodgson, A. T.; Perino, C. *Quantifying pollutant emissions from office equipment*; CEC/CARB University of California, Berkeley, 2009. http://www.osti.gov/bridge/product.biblio.jsp?osti_id=918677

**TITLE: Toxicity of fresh and aged semi-volatile and non-volatile PM**

**PROBLEM:** Many Californians live in nonattainment areas for fine particulate matter (PM). In all of these areas, organic material contributes a large fraction of the fine PM. Motor vehicles are important sources of organic PM. Organic PM is comprised of primary organic aerosol (POA, particle mass directly emitted from sources such as motor vehicles) and secondary organic aerosol (SOA, particle mass formed in the atmosphere from oxidation of gas-phase precursors). Upon their release from their sources, particularly anthropogenic sources such as motor vehicles that are abundant in Southern California, the multi-pollutant mixtures of vehicular exhaust, consisting of PM, semivolatile and volatile vapors and gases, undergo atmospheric processing and their physical, chemical and toxicological properties also evolve with the changing ambient conditions. Field measurements indicate SOA dominance, even in heavily urbanized areas; for example, the recent SOAR-1 campaign estimated that around 75% of the organic PM in Riverside is SOA. Previous studies have examined the toxicity of the fresh primary PM emissions from motor vehicles; however, fresh emissions may only dominate exposure in near roadway environments. Little is known about the toxicity of aged vehicle emissions.

**PREVIOUS WORK:** Recent research has demonstrated the dynamic nature of organic aerosol emissions from motor vehicles. Within seconds of leaving the tailpipe, there are dramatic changes in gas-particle partitioning of semivolatile organic (SVOC) materials. For example, research from the Southern California Particle Center (SCPC) has shown that in close proximity to traffic sources (i.e. freeways and busy roadways), rapid cooling and mixing of hot exhaust emissions with the real world mixture of pollutants in the urban atmosphere, causes particle formation by nucleation and condensation onto pre-existing seed particles. This process forms the majority of PM in the exhaust as measured by particle number and, in newer vehicles, even by mass; further atmospheric dilution of the exhaust causes evaporation of these species from the particles. Upon entering the atmosphere these freshly emitted species are exposed to atmospheric oxidants (e.g. $O_3$, OH radicals, and $NO_3$ radicals), which chemically alter emissions creating substantial secondary organic aerosol. These changes transform aerosol mass and chemical composition, but more importantly, alter the toxicity of the emissions. Recent studies by Carnegie Mellon University have also suggested that gas-phase SVOCs participate in photochemical reactions that contribute to secondary organic aerosols (SOA) after further aging and oxidation.[1] Additionally, the SCPC has shown that in the time scales of atmospheric transport within the LA Basin, atmospheric metals undergo redox cycling and are likely to be important in changing the toxicity of PM during atmospheric aging.[2] A recent study from the University of Southern California (USC) showed that aged ultrafine particles in the Los Angeles basin display greater dithiothreitol (DTT) activity and increased levels of endogenous reactive oxygen species (ROS) as compared to freshly emitted ultrafine particles.[3]

**OBJECTIVE:** The objective of this project is to measure the toxicity of fresh and aged aerosol emissions from motor vehicles.

**DISCUSSION:** The proposed two-phase research study will investigate the toxicity of fresh and aged motor vehicle emissions. Phase 1 will investigate toxicity of fresh and

aged emissions from individual vehicles operated over a standard test cycle on a chassis dynamometer. Phase 2 will investigate the toxicity of fresh and aged roadside emissions from a large vehicle fleet in field studies conducted in the vicinity of freeways in the Los Angeles area.

Task 1. The goal of this task will be to characterize the toxicity of fresh and aged emissions collected from individual vehicles. As part of an ongoing CARB/EPA/CRC supported project, Carnegie Mellon University will be quantifying the secondary organic aerosol production from vehicle exhaust. The experiments involve filling a smog chamber with exhaust from vehicles operated over standard test cycles using a chassis dynamometer. The emissions are then aged by exposing the chamber to either sunlight or artificial UV light. As part of the proposed project, Carnegie Mellon University will collect fresh and aged samples for toxicity analysis by USC. The research will characterize the toxicity of emissions from different classes of motor vehicle emissions (gasoline, diesel, smoker, low-emitter, etc).

Task 2. The goal of this task will be to characterize the toxicity of fresh and aged emissions from a large fleet of in-use vehicles at two roadway side sites. These sites will be in proximity of the CA-110 freeway, which is impacted almost 100% by light duty gasoline traffic, and the I-710, which has the highest ratio (up to 25%) of heavy-duty diesel vehicles in the Los Angeles highway network At each site the investigators will simultaneously collect fresh and aged emissions. Fresh emissions will be directly sampled. Aged emissions will be collected using an aerosol flow reactor that exposes the ambient aerosols to hydroxyl radicals. The integrated exposure will be equivalent to about one day of aging at typical atmospheric conditions. Particle collections will be conducted by means of state-of the–art techniques developed by the USC and Carnegie Mellon University groups. The collected PM samples will be used in a battery of in vitro tests, using assays developed by the SCPC such as DTT and ROS assays, which will determine their prooxidant and electrophile content and thus their overall redox activity.

**BENEFITS:** This project will provide important new knowledge and data for exposure and health effect assessments to fine particle mass. The linkage between the atmospheric evolution of fresh vehicular emissions, their physico-chemical characteristics, transformation, and resulting toxicity will be vital in the formulation of targeted regulatory efforts to reduce the human health impact of their emissions on human health. This research will therefore provide a strong scientific basis to develop cost-effective strategies to protect the public from toxic sources.

**CO-FUNDING:** This project will complement ongoing projects at SCPC, which are currently funded by U.S.EPA and ARB and will help evaluate toxicity using an array of in vitro assays. The SCPC studies characterize size distributions and composition of specific ambient particles related to specific sources in the laboratory. Substantial leveraging of costs will be realized with respect to site identification and access, provision of detailed chemical and physical analytical data, and direct comparisons to in vitro toxicology studies conducted through the SCPC. Also, the proposed study will be leveraged with an ongoing CARB/EPA/CRC supported project granted to Carnegie Mellon University to quantify SOA production from vehicle exhaust.

**COST:** $300,000 (*original submission requested $450,000*)

## REFERENCES:


1. Robinson, A.L., et al., 2007. Rethinking organic aerosols: Semivolatile emissions and photochemical aging. *Science*, 315(5816): p. 1259-1262.
2. Majestic, B.J., J.J. Schauer, and M.M. Shafer, 2007. Application of synchrotron radiation for measurement of iron red-ox speciation in atmospherically processed aerosols. *Atmospheric Chemistry and Physics*, 7(10): p. 2475-2487.
3. Verma, V., Ning, Z., Cho, A.K., Schauer, J.J., Shafer, M.M., Sioutas, C. 2009. Redox activity of urban quasi-ultrafine particles from primary and secondary sources, *Atmospheric Environ.* 43, 6360-6368.

**TITLE: Traffic-related pollution, DNA methylation and asthma in children living near sea ports**

**PROBLEM:** Asthma is the most common chronic disease among children in the United States affecting 1 in 12 children.[1] Asthma is a heterogeneous disease such that different asthma phenotypes have been defined based on disease severity, allergic predisposition, and response to treatment with anti-inflammatory medications. The disease disproportionately affects inner-city children from low socioeconomic background.[1] The economic burden of childhood asthma on healthcare is high with over $1000 spent annually for each child with asthma in 2004. [2]

Children with asthma are the most vulnerable population to changes in traffic-related pollution (TRP), as *in vitro*, animal and epidemiologic studies have provided strong support that TRP affects asthma occurrence and exacerbations.[3] However, problems with translating findings from *in vitro* and animal studies to humans and less than optimal characterization of asthma phenotypes in epidemiologic studies make it difficult to fully understand the biological mechanisms of air pollution effects in asthma.

Asthma has a strong genetic basis and genetic variants contribute to increase asthma susceptibility from exposures to TRP. [4, 5] A growing body of evidence also indicates that air pollution could affect DNA methylation[6, 7] and thereby can alter gene expression. Thus, a study among children with asthma that accounts for genetic variability within subjects provides an excellent opportunity to evaluate the impact of changes in TRP in Long Beach areas (near seaports) due to ARB's implementation of the Goods Movement Emission Reduction Program on asthma progression and epigenetic changes in key genes in the oxidative/ nitrosative stress.

**PREVIOUS WORK:** The Breathmobile program at the Los Angeles County+University of Southern California Medical Center provides regular asthma care in accordance with national standards. Each Breathmobile is a mobile clinic that is staffed by a four-member team of asthma care specialists. For the proposed project, the investigators, affiliated with the University of Southern California (USC), will utilize one Breathmobile that covers Long Beach. An electronic database routinely tracks sociodemographic information, clinical data on asthma phenotypes, and other relevant outcome measures (e.g., lung function, skin prick tests for allergy). The investigators found that residential proximity to freeways is associated with difficult-to-control asthma in children. [8]

For the southern California Children's Health Study (CHS), the investigators have already conducted intensive TRP assessment in Long Beach (a CHS community). In 2009, samplers were used to collect and characterize fine (PM2.5), quasi-ultrafine (PM0.2) and coarse (PM10-2.5) PM mass and components (e.g., elemental carbon, total organic carbon, metals) at 34 locations in Long Beach (homes, schools and central sites) over a 4-week period and in two seasons. These data will enable estimating baseline residential exposures to these TRP using GIS-based land-use regression models that accounts for traffic proximity, meteorology, local elevation, population density, and other land use categories. An active research group of statisticians at USC are involved in developing statistical methods to evaluate single pollutant effects in multi-pollutant exposure setting and in understanding the synergism of such pollutants.

**OBJECTIVE:** The three main objectives of the project are: (1) to characterize the spatiotemporal concentration patterns of traffic-related PM mass and components to record the changes in TRP in the study community; (2) to examine the effects of changes in TRP on asthma progression (symptoms, lung function growth) and gene-specific DNA methylation in buccal and blood samples in asthmatic children; and (3) to further test whether change in TRP results in differential gene-specific methylations in children with various asthma phenotypes (i.e., mild vs. persistent, allergic vs. non-allergic, well-controlled vs. difficult-to-control asthma). This novel approach will facilitate understanding of the TRP effects on asthma progression and provide new insights into the TRP-mediated epigenetic influences on asthma progression.

**DISCUSSION:** Using the Breathmobile that provides asthma care to children living in Long Beach, the investigators plan to enroll 3 to18-year-old children with asthma and routinely follow these children over a two-year period. They will collect both buccal and blood samples at each visit to determine global and promoter-specific methylation in these biological samples. Because gene expression due to tobacco smoke in buccal epithelium has been shown to reflect expression in airway epithelium[9], non-invasively collecting buccal epithelium for DNA methylation is reasonable.

Clinical data (e.g., body mass index, allergy test results, lung function, asthma symptoms, and anti-inflammatory medication use) will be routinely documented in Asma-Trax electronic database. The investigators will also collect additional information on each child's time-activity pattern, indoor home characteristics (exposures to tobacco smoke, pets, molds; level of parental stress) at each visit using a questionnaire. They will characterize the spatiotemporal concentration patterns of traffic-related PM mass and components to record the changes in residential TRP using a mobile monitoring platform in the second year of the study.[10] Data already collected as part of the CHS will provide baseline TRP exposures at homes. Pollen exposure data will available from another funded project.

For gene-specific methylation, they will use the Illumina HumanMethylation27 BeadChip assay, which provides high throughput, genome-wide, quantitative measurements of DNA methylation at 27,578 CpG dinucleotides spanning 14,495 genes. They will conduct methylation assays on 200 asthmatic children. The selection of subjects will be optimized to represent different clinical asthma phenotypes (allergy, severity, response to treatment). For each subject, samples collected at study entry and end will be used in methylation assays to determine changes in DNA methylation. Blood samples from a subset of children will be utilized to compare TRP effects on DNA methylation in different cells (buccal and blood cells) and to compare DNA methylation between cells.

**BENEFITS:** The proposed study uses novel approaches to generate new data that will improve understanding of the linkages among TRP, DNA methylation and asthma progression in children. Evaluation of changes in DNA methylation at each specific CpG (methylation) site within subjects will control for genetic variations and will allow the investigators to evaluate the independent impact of TRP on gene-specific DNA methylation. Comparison of DNA methylation in buccal and blood cell DNA will allow us to compare methylation across tissues which are vulnerable to TRP mediated

oxidative/nitrosative stress. They will also be well-positioned to evaluate whether different size-cuts and components in PM have different effects on asthma progression and DNA methylation. As the proposed project will provide information on the health effects of PM on a sensitive population of children, the ARB will be able to assess the health impacts of the air quality standards. Finally, the study will provide data to assess whether changes in TRP due to regulatory improvements in air quality resulted in reduction of asthma-related morbidity in children living near seaports.

**CO-FUNDING:** Operational costs for the Breathmobile Program are provided by the LAC+USC Medical Center. As part of the southern California Children's Health Study, data on different PM size-cuts and components in Long Beach is currently being analyzed ($485,116, NIEHS). Another funded project ($900,000, EPA) will measure pollens in Long Beach during 2010-2011 and could help predict pollen exposure in future using CMAQ and MEGAN modeling systems. The proposed project will leverage substantial exposure and clinical data from these funded projects.

**COST:** $550,000

**REFERENCES:**


1. Moorman JE, Rudd RA, Johnson CA, et al. National surveillance for asthma--United States, 1980-2004. *MMWR Surveill Summ* 2007; 56(8):1-54.
2. Kamble S, and Bharmal M. Incremental direct expenditure of treating asthma in the United States. *J Asthma* 2009; 46(1):73-80.
3. Salam MT, Islam T, and Gilliland FD. Recent evidence for adverse effects of residential proximity to traffic sources on asthma. *Curr Opin Pulm Med* 2008; 14(1):3-8.
4. Salam MT, Gauderman WJ, McConnell R, et al. Transforming growth factor- 1 C-509T polymorphism, oxidant stress, and early-onset childhood asthma. *Am J Respir Crit Care Med* 2007; 176(12):1192-9.
5. Salam MT, Lin PC, Avol EL, et al. Microsomal epoxide hydrolase, glutathione S-transferase P1, traffic and childhood asthma. *Thorax* 2007; 62(12):1050-7.
6. Baccarelli A, Wright RO, Bollati V, et al. Rapid DNA methylation changes after exposure to traffic particles. *Am J Respir Crit Care Med* 2009; 179(7):572-8.
7. Breton CV, Byun HM, Wenten M, et al. Prenatal tobacco smoke exposure affects global and gene-specific DNA methylation. *Am J Respir Crit Care Med* 2009; 180(5):462-7.
8. Huynh P, Salam MT, Morphew T, et al. Residential proximity to freeways is associated with uncontrolled asthma in inner-city Hispanic children and adolescents. *J Allergy (Submitted)* 2010.
9. Sridhar S, Schembri F, Zeskind J, et al. Smoking-induced gene expression changes in the bronchial airway are reflected in nasal and buccal epithelium. *BMC Genomics* 2008; 9:259.
10. Kozawa KH, Fruin SA, and Winer AM. Near-road air pollution impacts of goods movement in communities adjacent to the Ports of Los Angeles and Long Beach. *Atmos Environ* 2009; 43(18):2960-2970.

**TITLE: Zero-energy air purification materials to reduce the exposure of Californians to harmful air pollutants**

**PROBLEM:** Ozone ($O_3$) is associated with numerous adverse effects on the human respiratory system, and with premature mortality.[1-5] Efforts to reduce population exposures to ozone have focused on outdoor air, even though a major fraction of total exposure to $O_3$ occurs indoors.[5-8] In studies involving 2,500 residences in seven cities, indoor exposure accounted for 43% to 76% of total daily exposure to $O_3$, with a mean of 60%.[5] Although indoor $O_3$ concentrations are typically 20% to 70% of outdoor levels, the high indoor contribution to exposure stems from the fact that Californians spend an average of 18 hours indoors for every hour spent outdoors.[9] At risk populations, e.g., infants and the elderly, spend an even greater amount of time indoors.

$O_3$ is also a driver of indoor chemistry and leads to the formation of oxidized reaction products which can be toxic, such as formaldehyde.[6] Cumulative molar intake of these products can be as much as twice the intake of $O_3$.[5]

Indoor exposures are also responsible for 70% of cumulative exposure to a wide range of organic hazardous air pollutants (OHAPs).[10] The proposing investigator's team has estimated cumulative cancer risks associated with exposures to just 12 OHAPs in Houston of nearly $10^{-3}$, with risks dominated by indoor exposures.[11] Thus, *indoor controls are a potential, but largely unexplored, strategy to reduce population exposures to $O_3$ and its reaction products, as well as to OHAPs*.

**PREVIOUS WORK:** Activated carbon (AC) has been used extensively to control OHAPs, and has also been observed to remove $O_3$ from air.[12-16] Although field data are sparse, $O_3$ removals of 50% to 95% have been observed 1 to 3 years into AC bed operation for several large buildings.[15, 16] Recent experiments at the University of Texas (UT) have also shown that low-cost and less energy-intensive activated carbon fiber mats can be strategically placed on walls to passively remove $O_3$ from indoor air.[17] Ongoing studies at UT also indicate that substantial $O_3$ removal can be achieved with more acceptable materials, such as clay wall coverings, without concomitant formation of $O_3$ reaction products. Through the use of selective materials placed in areas with relatively high but natural air flows (no additional energy needed) the investigators have shown experimentally and through modeling that occupant exposures to $O_3$ in homes can be reduced by over 50%, with up to 30% reduction in total $O_3$ exposure. The proposing investigator's team has further shown no net changes in material performance over six months in actual field conditions. Finally, their ongoing research also suggest that some OHAPs are effectively removed from some indoor materials, although more work is needed to ascertain long-term desorption.

**OBJECTIVE:** It should be possible to use aesthetically acceptable materials as zero energy air purification (ZEAP) materials (hereafter referred to as ZEAPs) to reduce population exposures to $O_3$, $O_3$ reaction products, and OHAPs. The *objective of this study* is to explore the use of ZEAPs for substantially reducing population exposures to $O_3$, $O_3$ reaction products, and OHAPs. This effort will serve as an expansion of current research (additional ZEAPs and inclusion of OHAPs) being completed at the University of Texas at Austin.

**DISCUSSION:**
Task 1. Testing will include both small (48-L electro-polished stainless steel) and large (70,000-L stainless steel) chambers. Small chamber experiments will follow protocols described by Poppendieck *et al*.[18] for $O_3$ deposition and Won *et al*.[20-21] for OHAP sorption. Each of six ZEAPs will be tested to ascertain reactivity with $O_3$, degree and nature of reaction products, and sorptive uptake and release of OHAPs. Three promising ZEAPs will be selected for large chamber testing of $O_3$ and OHAP removal. Three OHAPs will be studied: benzene, *p*-dichlorobenzene, formaldehyde. A semi-factorial experimental plan will explore effects of variations in RH and mixing intensity.
Task 2. Chamber results will be evaluated in a house (UTest House). Experiments will be completed during the $O_3$ season with four one-month conditions (no ZEAP + each of three ZEAPs in series). Two complete walls in the living area will be equipped with a ZEAP. Air exchange rate will be measured using $CO_2$ releases and decay on an intermittent basis. Indoor (near HVAC return grill) and outdoor $O_3$ concentrations will be measured on a continuous basis. These data will allow determination of $O_3$ decay rates due to reactions with materials in the house and, by differencing from background, increases in reaction-based decay rates due to each ZEAP. On three occasions during each condition a release of OHAPs will be made with analysis of decay rates to determine sorption parameters.

Task 3. Information regarding spatial variations in residential building stock, outdoor $O_3$ concentrations, and indoor OHAP concentrations will be coupled with data collected for this study to complete a novel assessment of ZEAP materials for population $O_3$ and OHAP exposure reductions. The assessment will include net benefits, costs, and continued engineering challenges. The Sacramento metropolitan area will be considered, but protocols will be applicable to other cities.

**BENEFITS:** This study has direct relevance to the health of Californians, the majority of which live in $O_3$ nonattainment areas. The health benefits derived from reduced $O_3$ exposure will have substantial and positive economic implications in California. Applying monetary health benefit data for incremental $O_3$ reductions[1], a very rough estimate of benefits approaching $10 billion/year is possible by retrofitting every home and school/classroom in California nonattainment areas with ZEAPs that reduce indoor $O_3$ levels by 50%, achievable with at least two ZEAPs that the investigators have tested (activated carbon (AC) and clay wall coverings). The estimated cost using AC is $100 to $200 million/year (benefit/cost ratio of between 50:1 to 100:1). Similar economic analyses are more difficult for OHAPs because of uncertainties in the health effects of low-level long-term exposures. However, given that indoor environments dominate the exposure of Americans to OHAPs and that cumulative cancer risks are relatively high, it is reasonable to assume that substantial long-term health benefits would be gained by effective application of ZEAPs for OHAP removal.

**CO-FUNDING:** This study will benefit from infrastructure developed for past research at UT. The principal investigator has extensively researched $O_3$ and OHAP interactions with indoor materials, with funding from the American Chemistry Council, British Petroleum, the U.S. Department of Defense, U.S. EPA, and others.[18-21] Two current projects funded through the State of Texas Advanced Research Program and the US

Green Building Council will end in several months. The proposed study would allow continuation of those studies and future leveraging from others, e.g., the National Science Foundation.

**COST:** $254,205

**REFERENCES:**


1. Levy, J.I., *et al*. (2001), *Environ. Health Perspectives*, 109: 1215-1226.
2. Bell, M.L., Peng, R.D., Dominici, F. (2006), *Environ. Health Perspectives*, 114: 532-536.
3. Ito, K., De Leon, S.F., Lippmann, M. (2005), *Epidemiology*, 16: 446-457.
4. Trische, E.W., *et al*. (2006), *Environ. Health Perspectives*, 114: 911-916.
5. Weschler, C.J. (2006), *Environ. Health Perspectives*, 114: 1489-1496.
6. Weschler C.J. (2000), *Indoor Air*, 10: 269-288.
7. Zhang, J.F., Lioy, P.J. (1994), *Indoor Air*, 4: 95-105.
8. Liu, L.-J., *et al*. (1993), *Environ. Health Perspectives*, 101: 318-324.
9. Klepeis, N.E., *et al.* (2001), *J. of Exposure Analysis and Environ. Epidem.*, 11: 231-252.
10. Loh *et al*. (2007), *Environmental Health Perspectives*, 115(8): 1160-1168.
11. Hun, D. *et al*. (2009), *Environmental Health Perspectives*, 117(12): 1925-1931.
12. Dusenbury, J.S., Cannon, F.S. (1996), *Carbon*, 14: 1577-1589.
13. Lee, P., Davidson, J. (1999), *American Industrial Hygiene Association Journal*, 60(5): 589-600.
14. Metts, T.A., Batterman, S.A. (2006), *Chemosphere*, 62: 34-44.
15. Shair, F.H. (1981), *ASHRAE Trans.*, 87: 116-139.
16. Weschler, C.J., Shields, H.C., Naik, D.V. (1994), *ASHRAE Trans.*, 100: 1121-1129.
17. Kunkel, D.A, *et al*. (2010), *Building and Environment*, 45(2): 445-452.
18. Poppendieck, D., *et al*. (2007), *Atmos. Environ.*, 41: 3166-3176.
19. Poppendieck, D., Hubbard, H., Weschler, C.J., Corsi, R.L., (2007), *Atmos. Environ*, 41: 7614-7
20. Won, D., Corsi, R.L., and Rynes, M. (2001), *Indoor Air*, 11(4): 246-256.
21. Won, D. Corsi, R.L., and Rynes, M. (2000), *Environ. Sci. & Technol.*, 34(19): 4193-4198.

## APPENDIX B: Concepts Recommended for Emissions Reductions

### Table of Contents

**TITLE: Characterization and mitigation of volatile organic compound emissions from dairy silage sources**

**PROBLEM:** Silages have been known to be a major source on dairies for the emissions of volatile organic compounds (VOCs). Alcohols and aldehydes, including methanol, ethanol, iso-propanol and acetyl-aldehyde, are the major components of the VOCs emitted from silages. Alcohols account for 70-80% of VOCs emitted from the silages. They are bacterial fermentation products during ensilage fermentation processes. The types and contents of alcohols and aldehydes in the silage directly influence the emission rates and total emissions of these compounds. In order to estimate or predict the VOC emissions from various silage sources, the contents of alcohols and aldehydes in the silage must be known. However, very few data are available showing the types of alcohols and aldehydes and their contents in the silages used on California dairies, which are largely influenced by silage crop, crop maturity, moisture content, bulk density and bacterial inocculum addition. Research is urgently needed to characterize the various silages used on California dairies to determine the alcohols and aldehydes and their contents and compare the different silage crops, storage and management practices used on dairies so that recommendations can be developed for the dairy industry to make silages with reduced alcohol and aldehydes contents and emissions.

**PREVIOUS WORK:** An ARB-funded project on the development of a process-based VOCs emission model for dairy farms was recently completed.[1] A computer model was developed for predicting the emissions of alcohols from corn and alfalfa silages. More modeling work is being conducted with a research grant from National Milk Producers Federation to develop an emission model for predicting the emission of acetyl-adehyde from silages as our research results indicated that besides alcohols, acetyl-aldehyde is another major compound emitted from the silages and has high reactivity for ozone formation. The contents of alcohols and aldehydes in silage are an important input parameter for the emission models. However, there is no database available on the characteristics and alcohol and aldehydes contents of various silages that are used on California dairies and it is difficult to apply the emission models for estimating the emissions from dairies. Previous research demonstrated that corn and alfalfa silages have quite different types and contents of alcohols and aldehydes. A literature review revealed that the control and modification of the silage production processes could lead to an effective strategy for reducing or preventing the alcohol and aldehydes production in silages and consequently reducing their emissions. To support emissions estimates and reductions, investigators need to develop a database for the characteristics of various silages used on commercial dairies in California and apply emissions models to estimate the alcohol and aldehydes emissions from dairies of different locations and climatic conditions. Investigators also need to develop recommendations for reducing or preventing the alcohol generation in the silages.

**OBJECTIVE:** The main objectives of this project are to: (1) collect information and data on the silage production and management practices and characterize various silages produced on California dairies; (2) evaluate effects of different ensilage practices (e.g., inoculated versus not inoculated) on silage characteristics and alcohols and aldehydes produced; (3) determine the potential of alcohol and aldehydes emissions from different

silages; and (4) develop strategies for reducing or preventing the generation of alcohols and aldehydes during the ensiling process and consequently reducing their emissions.

**DISCUSSION:** In order to assess the silage crops and ensilage practices used on commercial dairies, investigators will first conduct a survey for the dairies located in different parts of the State. Based on the survey results, investigators will select 30-40 dairies that will cover a range of different silages and climatic conditions. Then researchers will work closely with these dairies to collect information and data when their silages are made and collect samples from the silages using scientific protocols. The silage samples will be analyzed for alcohol and aldehydes species as well as moisture content, pH, volatile solids, lactic acid and volatile fatty acids. For each dairy, the silage samples will be taken at different times of the year so that the changes in silage over time can be quantified. Based on the chemical analysis results and the physical configurations of silages, potential emissions of alcohols and aldehydes from these silages will be calculated using our recently developed emission models. To investigate the effects of silage crop characteristics and ensilage process parameters, controlled experiments will be performed with different silage crops (e.g. corn, alfalfa and ryegrass) with different bulk densities, temperatures and moisture contents. Both laboratory and field experiments will be conducted. The characteristics of the experimentally produced silages will be compared with those produced on the dairies. In all experiments, bulk densities will be applied in the ranges commonly applied on commercial farms. Different moisture contents will be chosen based on different maturity stages of crop. The effect of using different doses of *Lactobacillus* and *Enterococcus faecium* strains on the characteristics of silages will also be studied. Recommendations for best silage making practices to reduce the generation of alcohols and aldehydes will be developed for the dairy industry. Investigators will collaborate with the dairy producers and silage production companies so that the results of this research are relevant to the dairy practices and the developed recommendations for best silage making practices can be both scientifically sound and practically useful.

**BENEFITS:** This work addresses the critical need to estimate and predict the VOC emissions from commercial dairies and develop effective strategies for reducing the VOC emissions from silage sources and consequently improving the air quality of the State. The expected outcome of this research will include the new scientific knowledge and database for the silage production and management practices currently used on commercial dairies and the types and contents of alcohols and aldehydes present in various silages and recommendations for best methods and practices for producing and managing silages with reduced alcohol and aldehydes emissions.

**CO-FUNDING:** Prospective investigators have a complementary project funded by National Milk Producers Federation on developing the VOC emission models for dairies.

**COST:** $300,000

**REFERENCES:**

1. Zhang, R. et al. 2010. “Process-based farm emission model for estimating volatile organic compound emissions from California dairies.” A final research report (contract 05-344) submitted to the California Air Resources Board. http://www.arb.ca.gov/research/apr/past/05-344.pdf

**TITLE: Developing, validating and implementing a process modeling system for California agriculture greenhouse gas inventories**

**PROBLEM:** Agriculture represents a significant source of methane and nitrous oxide. The traditional approach of using simple emission factors for agricultural emission inventories is limited due to the complex temporal and spatial variability of soil, crop, climate and management factors that control GHG emissions. New methodologies linking GIS databases with process-based models are being used to bring complex agroecosystems into a computable framework for building emission inventories and for assessing the impact of alternative management practices on net soil carbon (C) storage and GHG emissions. While the International Panel on Climate Change suggests process modeling (referred to as TIER 3 method) can improve accuracy of emission inventories, it is important to calibrate this method to specific cropping systems, perform model validation to estimate model structural uncertainties and to understand model sensitivity to inputs and overall uncertainty (upper and lower bounds).

**PREVIOUS WORK:** Over the past 20 years, the DNDC process-based model has been developed to predict impacts of various farming practices including fertilization, crop residue management and manure amendment on C and nitrogen (N) biogeochemical cycles and trace gas emissions ($CH_4$ and $N_2O$) for forests and agro-ecosystems. DNDC was constructed with two components to reflect the two-level driving forces that control geochemical and/or biochemical processes related to C and N fluxes. The first component, consisting of the soil climate, crop/tree growth and decomposition sub-models, predicts soil temperature, moisture, pH, redox potential (Eh) and substrate concentration profiles (ammonium, nitrate, dissolved organic carbon) based on ecological drivers (e.g., climate, soil, vegetation and anthropogenic activity). The second component, consisting of the nitrification, denitrification and fermentation sub-models, predicts NO, $N_2O$, $CH_4$ and ammonia ($NH_3$) fluxes based on the soil environmental variables.

With on-going funding from California Energy Commission (CEC), California Department of Food and Agriculture (CDFA), Packard Foundation and ARB, field studies to measure soil carbon dynamics and $N_2O$ emissions for a wide range of California crops. These projects are collecting critical data for model calibration and validation. A project funded by the United States Department of Agriculture's (USDA) Natural Resources Conservation Service (NRCS) from 2008-2010 developed detailed databases on rice production systems, validated the DNDC model for rice $CH_4$ emissions, developed an initial inventory of net GHG emission from California rice, and has evaluated several alternative water and straw management practices for reducing GHG emission. Prior to this NRCS project, a scoping project was completed with CEC PIER funding (see report CEC 500-04-038) to assess carbon sequestration and GHG emission from agricultural soils in California. With funding from CEC, USDA and National Milk Producers Federation a new version of DNDC, called Manure-DNDC, has been developed to quantify air emissions ($CH_4$, $N_2O$, NO, $NH_3$, $CO_2$ and VOCs) from dairy systems.

**OBJECTIVE:** The goal is to develop, demonstrate and transfer to ARB a framework for collecting GIS and agricultural management data, link these data in a GIS framework with DNDC process models (cropland and dairy versions) for agricultural $N_2O$, $CO_2$ and $CH_4$ emission inventories, and develop an explicit uncertainty budget due to both structural (derived from model validation) and scaling (unknowns in model input data for inventory, e.g. soils, agricultural management, crops, etc). Therefore, investigators will undertake to meet the following objectives: (1) collect $N_2O$ emissions data from dairy drylots and manure solids treatment/storage systems, (2) develop GIS databases for statewide GHG modeling, (3) compile agricultural management databases, (4) assess model uncertainties (both structural and scaling) through model validation, (5) perform comparison of DNDC and DAYCENT models, (6) compile GHG emission inventory for California agriculture, and (7) work with ARB inventory staff on use and updates to the modeling system.

**DISCUSSCION:** The task list for this research is as follows.

**1**: An FTIR system and INNOVA portable gas analyzer will be used to collect $N_2O$, $CO_2$ and $CH_4$ flux data from manure solids (storage, treatment and compost piles) and drylots. The INNOVA unit samples six gasses continuously at ppb detection levels. These field data will be collected at the NAEMS site and an additional dairy in California.

**2:** Build GIS databases on soils (NRCS SSURGO), climate (CIMIS stations) and crops (DWR and NASS CDL). For each crop field, probability distribution functions (PDFs) for SOC, bulk density, pH, and texture will be calculated from the soil surveys. Daily precipitation, temperature, wind speed, and solar radiation will be compiled for each field using CIMIS with cokriging.

**3**: Collect and compile regional-specific crop growth/yield (calibrate growth model) and management data (tillage, irrigation, fertilizer, crop residue management, cover crops, etc). Data sources include UCCE Cost/Return Studies, UC Extension, and commodity groups. GIS data will be used to characterize growing regions by soil, climate and cropping systems (e.g. truck crops, grains, etc). Application of remote sensing for mapping and monitoring rice area and water management will be demonstrated.

**4:** Validate and calibrate DNDC crop growth model. Since accurate crop growth modeling is critical for process modeling, investigators will calibrate/test crop growth (physiology/phenology) submodels in DNDC based on data collected in Task 3.

**5**: Validate DNDC using data from Task 1 and from other projects collecting $N_2O$ emissions from land application of Manure (e.g. ARB- and Waste Board- funded project with Dr. Will Horwath, Dr. Goorahoo ARI funded project).

**6**: Compare DNDC and DAYCENT models for cropland sites. This comparison will provide insight into relative model uncertainties. Both models are extensively used for estimating GHGs emissions, and a quantitative evaluation of the differences will provide a common base for comparing the inventories and uncertainties.

**7**: Run validated DNDC and Manure-DNDC models to compile $CO_2$, $N_2O$ and $CH_4$ agricultural inventory for California using the integrated GIS databases (Task 2) and crop models (Task 3).

**8**: Quantify sensitivities and uncertainties in inventory estimate due to both model precision (structural uncertainty) and scaling up using GIS data. Uncertainties will be quantified using a series of statistical approaches. DNDC model structural uncertainty will be derived from field validation analyses (see discussion in previous work and Co-funding sections). Scaling uncertainty will be derived using Monte Carlo analyses and the PDFs from Task 2. Model sensitivity will identify critical input data needed to minimize uncertainties and guide future data collection efforts.

Throughout these tasks investigators propose to work with ARB inventory staff for training, model validation, and updating the modeling system for future inventories. The modeling system will a living system that will improve over time as new research is completed, improved spatial data are available and future improvements in the model derived from additional validation.

**BENEFITS:** Successful completion of this study will deliver spatial databases on crop model parameters (including regional management data), a GIS database design and a process modeling framework for future greenhouse gas emission inventories for California agriculture. These databases and tools can also be used to examine opportunities for mitigation and carbon offsets. Carbon offset opportunities would benefit California farmers, who represent 400 different commodities and $22 billion in state revenue. In addition to providing an inventory for land-based GHG emissions, the results of this project will help provide potential incentives (through carbon offsets) for land owners to change to land management practices that reduce GHG emissions and provide other environmental co-benefits. There are significant opportunities to achieve permanent reductions in $N_2O$ and $CH_4$ emissions.

**CO-FUNDING:** Environmental Defense Fund (EDF) will provide matching funding from Packard Foundation and anticipated CDFA Block Grant funding for validating the DNDC model and calibrating crop growth submodels in DNDC. In addition, through existing projects funded by ARB, CEC, CDFA and Packard Foundation, $N_2O$ data are being collected across a broad swath of cropping systems in California. DNDC model validation effort are currently funded for the CEC and CDFA projects, validation of the model for the $N_2O$ data collected by the ARB project is not currently funded. This task will expand the current validation efforts to include the data collected under the on-going ARB project led by Dr. Will Horwath.

**COST**: $300,000 (plus $100,000 match from EDF)

**TITLE: Investigation of Combined Aerodynamic Modifications to Reduce Emissions from the Current Heavy Duty Fleet**

**PROBLEM:** In addition to meeting criteria pollutant standards, ARB is responsible for meeting ambitious greenhouse emission reduction targets. In collaboration with stakeholders and agencies throughout the state, ARB is actively exploring cost-effective strategies, both regulatory and voluntary. The 700,000+ heavy duty-trucks in California are a vital part of our State's economy and freight system; however, they consume significantly more fuel—producing more criteria pollutants and GHG emissions—per vehicle than light duty vehicles due to their aerodynamic profile, weight, and distances traveled. Advanced aerodynamic modifications to reduce fuel consumption from the heavy duty fleet could help reduce emissions from this sector without adversely affecting our state's economy.

**PREVIOUS WORK:** Significant development of aerodynamic fairings, skirts and other devices has been undertaken in both the public and private sectors, resulting in many such devices currently on the market that can be used by truckers to improve fuel economy. These devices have been the subject of much testing, including research by federal agencies and manufacturer verification via the SmartWays program. However, little work has been done to investigate and quantify the benefits from combinations of multiple devices used simultaneously.

Current ARB rules require use of technologies that can provide 5 percent or more fuel economy improvement. This project would investigate the possibility that even greater fuel economy improvements could be achieved by use of various combinations of aerodynamic technologies.

**OBJECTIVE:** The U.S. EPA SmartWay Program has verified several individual aerodynamic technologies that reduce fuel consumption and emissions. Some of the verified technologies focus on diverting air flow away from the trailer's axle while other technologies have focused on air flow improvements at the rear of the trailer. However, there has been very limited work in evaluating the benefits of using several technologies together that may provide synergistic benefits. Also, many trailers are designed with various types of equipment that require modifications to some of the verified aerodynamic technologies, such as refrigeration units or under-mounted tool boxes and loading ramps. However, it is not well understood how the necessary modifications to the technologies affect their aerodynamic performance. In addition, the current SmartWay test method to verify technology is the SAE 1321 test method, which is very costly and time consuming. This project will investigate development of a new test method that would utilize Portable Emission Measurement System (PEMS) or similar technologies to determine both fuel economy benefits, through carbon emission analysis, as well as criteria emission benefits. The evaluation will probe the following:

- Potential benefits of using multiple SmartWay verified aerodynamic technologies on trailers
- Affects of modifying verified aerodynamic technologies to accommodate various types of trailer equipment

- Correlation of calculating fuel consumption utilizing PEMS compared to methods established by the SAE 1321 test method
- Evaluating criteria emission benefits of aerodynamic technologies utilizing PEMS

**DISCUSSION:** The proposed project will involve an evaluation of aerodynamic devices in multiple combinations on multiple platforms for increased reductions of greenhouse gases from on-highway trucks. These configurations would be evaluated through detailed on-road testing using PEMS technology or other mobile equipment such as a Mobile Emissions Laboratory (MEL). The results of the on-road testing would then be utilized to quantify and characterize the emissions reductions for the different configurations tested.

**BENEFITS:** Results from this study will ultimately reduce our dependence on petroleum-based fuels, improve air quality, and aid in mitigating our green house gas contribution.

**COST:** $300,000

**TITLE: Probing the intrinsic ability of particles to generate reactive oxygen species**

**PROBLEM:** Oxidative stress mediated by reactive oxygen species (ROS) is a leading hypothesis for the mechanism by which particulate pollution contributes to a range of illnesses, including asthma and cardiovascular mortality. ROS are generated endogenously in response to inhalation of particulate matter (PM), but the "exogenous" ability of the particles themselves to generate ROS may also be important. This work will elucidate the ability of particles to generate ROS under physiological conditions, delineate the components in particles responsible for "exogenous" ROS formation, and clarify the interplay between $H_2O_2$ and OH. Understanding the particular components in PM that lead to adverse health effects is essential to formulating targeted control strategies to reduce PM related morbidity and mortality.

**PREVIOUS WORK**: A series of studies have reported $H_2O_2$ and related ROS in fine and/or coarse mode aerosols. Measurements in urban areas indicate averages for $H_2O_2$ or $H_2O_2$ combined with other ROS ranging from 2 to over 200 ng/m$^3$.[1-8] In a detailed study using simultaneous measurements of gas and aerosol $H_2O_2$, aerosol mass and ambient relative humidity, our group found that $H_2O_2$ associated with particles exceeded the expected value from Henry's law by an average factor of about 700.[2] Hydroperoxides measured in these field campaigns are generated during the extraction procedure. Some particles stop generating $H_2O_2$ after an hour, while others continue to generate $H_2O_2$ for days.[3, 8]

OH radicals are more reactive than other ROS. As a result, their estimated concentrations in condensed phases are generally low. Like $H_2O_2$, they undoubtedly partition between the gas and condensed phases, and are also generated by aerosols.[9-12] Their primary source in the dark may be breakdown of $H_2O_2$ catalyzed by transition metals,[10, 11] although this remains to be determined.

In *in vitro* studies, hydrogen peroxide and OH radicals have been shown to damage lung epithelial cells at levels well below those associated with ambient samples.[13-16] Additionally, an *in vivo* study[17] showed that two-hour exposures to $H_2O_2$ dissolved in ammonium sulfate particles, at levels similar to those associated with urban particulate matter,[18] produced symptoms associated with respiratory distress, while gas-phase peroxides or particles alone elicited minimal responses.

Short duration exposures, such as those made in previous work, usually use concentrated air pollution; statistically significant responses for ambient levels of particulate $H_2O_2$ are notable. While this result strongly suggests that $H_2O_2$ generation itself may be toxic, it remains unclear how the $H_2O_2$ and ROS generation activity intrinsic in the particles (exogenous, or 'exo-ROS') compares to ROS produced in vivo in response to particles depositing in the lungs. The proposed study's measurements will significantly constrain exogenous ROS. Although direct measurements of endogenous $H_2O_2$ and ROS (endo-ROS) production are beyond the scope of this project, efforts will be made to make quantitative comparisons of exo- and endo-ROS throughout the full proposal preparation and project stages. The combined approach will be continuous monitoring of on-going animal studies and efforts to develop or catalyze separate

studies or collaborations to address this key question. An important related question is whether the particles or components that generate the most exo-ROS also induce higher levels of endo-ROS.

**OBJECTIVE**: Objectives of this investigation are to (1) determine the strength of ROS production intrinsic in ambient particles, (2) probe the sources and relative strengths of ROS production via (speciated) transition metals and quinones, (3) probe the balance between $H_2O_2$ and OH and the underlying mechanism(s) of ROS generation, and (4) elucidate the sources of quinones in particles.

**DISCUSSION**: Samples will be collected on Teflon filters and polyurethane foam plugs. Aerosol-phase OH and hydroperoxides will be extracted in physiologically relevant solutions with adjusted ionic strength, pH and with added electron donors such as ascorbate, and control solutions. Hydroperoxides will be quantified using high performance liquid chromatography (HPLC)-fluorescence.[2] The HPLC-*p*-hydroxybenzoate method will be used for OH quantification,[10, 12] requiring an additional HPLC. Aerosol mass and about 16 soluble trace elements will also be quantified.

Quinones and related organics will be extracted, concentrated, and analyzed by Gas Chromatography-Mass Spectrometry (GC-MS) for nine quinones, eleven PAHs, $C_{20}$-$C_{32}$ n-alkanes, levoglucosan, cholesterol and selected hopanes/steranes.[19] Results will also be combined with the OH, peroxide and elemental measurements in a multivariate analysis to evaluate the relative contributions of the measured components to the ROS. The target compounds include markers for engine exhaust, leaf abrasion, biomass combustion, meat cooking and combustion,[20] and will be used in a Positive Matrix Factorization analysis[21] to evaluate the sources of quinones as well as other ROS active species such as transition metals.[8]

Samples will be collected at selected sites in Fresno and Los Angeles, areas with rather different PM characteristics, in on-going measurements and intensives. To the extent that it makes sense, investigators will join with other researchers, to create synergies where possible. In addition, on-going measurements will be performed on in-lab source materials such as diesel exhaust to address focused questions.

Synthetic mixtures containing quinones and metals to produce peroxides and OH will be measured to test the hypothesized mechanisms, at concentrations reflecting those measured in field sample extracts and at higher concentrations similar to those in particles. The role of electron donors that may be present in PM (such as phenol), and endogenous electron donors (such as ascorbate) will be probed.

**BENEFITS**: The ROS mechanism work proposed here will help unravel the cause of particle-mediated damage to human health. The most likely sources of ROS are transition metals, quinones and possibly other unknown organics in the particles themselves. These species are also prime candidates responsible for eliciting endo-ROS formation. To date, studies have focused on limited segments of the phenomenon, such as measuring OH or $H_2O_2$ separately and their relationships to transition metals or quinones. This study proposes to take a comprehensive approach to understanding particulate formation of ROS, by monitoring $H_2O_2$ and OH radical generation as well as

transition metals and organics, including quinones, in ambient aerosol samples and laboratory-generated test aerosols. This will shed light on the question of the degree to which $H_2O_2$ is in steady state, i.e., continuously formed and destroyed, thus potentially releasing large quantities of OH; or if it is a stable end product. The detailed organic analysis in addition to specific source testing will allow us to attribute the active components to their sources. The work determining the active agents in ROS generation will advance and inform the search for species that generate exo-ROS, and possibly elicit endo-ROS as well.

**CO-FUNDING**: Two current grants at Fresno State can be used to leverage the project by providing funding to support up to four research students (salary and travel) and some of the supplies and consumables that would be required. Two of these students would be supported through Fresno State's subcontract for the NOAA-funded Interdisciplinary Scientific Environmental Technology (ISET)-Cooperative Science Center (CSC) Center ($446,000; 9/01//06-8/31/11) and two through the National Science Foundation (NSF)-funded Geosciences METRO Center ($1.4M; 09/01/09-08/31/13). A renewal of the National Oceanic Administration (NOAA) center will be pursued, as will other potential co-funding opportunities.

A potential collaboration with Professor Anastasio of UC Davis making measurements of OH radicals in the field will be pursued during the proposal stage. Prof. Anastasio's extensive expertise in this area will be a valuable addition to this project, and the collaboration will provide intellectual synergies that will further advance the understanding of particle toxicity. Funds for Prof. Anastasio's part of the collaboration are not included in the proposed budget.

**COST**: $260,000

**REFERENCES**:


1. Hasson, A.S. and S.E. Paulson, (2003) *J. Aerosol Sci.* **34**: 459-468
2. Arellanes, C., S.E. Paulson, P.M. Fine, and C. Sioutas, (2006) DOI: 10.1021/es0513786.DOI: 10.1021/es0513786.
3. Paulson, S.E., C. Arellanes, and Y. Wang, (2009) CARB Report 93.pps.
4. Venkatachari, P., et al., AN 2007:262793.
5. See, S.W., Y.H. Wang, and R. Balasubramanian, (2007) ISI:000244903200003.
6. Hung, H.F. and C.S. Wang, (2001) ISI:000170683800005.
7. Venkatachari, P., P.K. Hopke, B.D. Grover, and D.J. Eatough, (2005) (and Erratum). ISI:000227517600003.
8. Wang, Y., C. Arellanes, D. Curtis, and S.E. Paulson, (2010) Concentrations and Sources of Coarse Mode Aerosol $H_2O_2$ in Southern California. (accepted for publication in Environ. Sci. Technol.)
9. Anastasio, C. and J.T. Newberg (2007) ISI:000246846400007.
10. Vidrio, E., H. Jung, and C. Anastasio (2008) Atmos. Environ. **18**: 4369-4379
11. Nico, P.S., B.M. Kumfer, I.M. Kennedy, and C. Anastasio, (2009) ISI:000260678700003.
12. Jung, H., B. Guo, C. Anastasio, and I.M. Kennedy, (2006) ISI:000235784800004.
13. Oosting, R.S., et al. (1990) Am. J. Physiol. **259**: L87-L-94
14. Holm, B.A., et al. (1991) Am. J. Physiol. **261**: C751-C-757
15. Brown, D., et al. (2004) Am. J. Physiol.-Lung Cell. Mol. Physiol. **286**: L344-L353
16. Li, N., M. Wang, T.D. Oberley, J.M. Sempf, and A.E. Nel, (2002) J. Immunol. **169**: 4531-4541
17. Morio, L.A., K.A. Hooper, J. Brittingham, T.-H. Li, R.E. Gordon, B.J. Turpin, and D.L. Laskin, (2001) Toxicology and Appl. Pharmacology. **177**: 188-199
18. Paulson, S.E., Y. Wang, and D. Curtis, *Generation of Reactive Oxygen Species by Particles: Relationship to Cardiovascular Disease*. 2009, California Air Resources Board: Sacramento. 39 pps.

19. Chung, M.Y., R.A. Lazaro, D. Lim, J. Jackson, J. Lyon, D. Rendulic, and A.S. Hasson (2006) Env. Sci. Tech. **40**: 4880-4886
20. Shrivastrava, M.K., R. Subramanian, W.F. Rogge, and A.L. Robinson, (2007) Atmos. Environ. **41**: 9353-9369.

**TITLE: Understanding primary organic aerosol volatility at atmospherically realistic concentrations for State Implementation Plan analysis**

**PROBLEM:** Recent emissions tests have determined that primary organic aerosol (POA) generated from combustion sources behaves like a series of semi-volatile compounds when the particulate phase concentrations range between 100 – 10,000 µg m-3. The data available for atmospherically relevant concentrations below 30 µg/$m^3$ are sparse and the data below 10 µg/$m^3$ are missing entirely. The simple absorption theory that appears to explain the behavior of gas-particle distribution of condensable organics at high concentrations may not be accurate at atmospherically relevant concentrations. It is likely that other processes such as chemical and physical adsorption onto elemental carbon and/or partitioning into the aqueous phase play significant roles at lower concentrations. The details of the primary organic aerosol partitioning need to be understood to predict the benefits of emissions control programs contained in the SIP and the impact of climate change on atmospheric organic aerosol pollution.

**PREVIOUS WORK:** Experiments in which exhaust from combustion sources is cooled to ambient temperature and then diluted have been used to study the semi-volatile nature of POA emitted from a simple diesel engine and flash vaporized motor oil.[1-3] Thermal denuders have also been employed to reheat the diluted exhaust to study the partitioning of the POA.[1] The resulting dataset has been used to generate "best fit" partitioning curves that have been extrapolated from the high concentration range (COA = 100–10,000 µg/$m^3$), where most of the experiments have been performed, to the atmospherically relevant range (COA = 1–30 µg/$m^3$) where almost no experiments have been reported. This situation is analogous to the extrapolation of SOA partitioning curves generated at high concentrations in smog chamber experiments to atmospherically relevant concentrations.[4] The SOA extrapolation was ultimately shown to be incorrect (5), and preliminary evidence suggests the POA extrapolation may also be incomplete (6). Recent light duty vehicle emissions testing carried out at the CARB Haagen Smit Facility examined POA partitioning under atmospherically relevant concentrations (COA = 1–10 µg/$m^3$).[7-10] New chemical analysis techniques were able to characterize ~20–30% of the POA present under these low concentration conditions. The majority of the identified POA was comprised of small oxygenated organic compounds with relatively high vapor pressures.[7] This contradicts the behavior predicted by the absorption theory. Rigorous absorption calculations failed to reproduce the observed partitioning behavior.[7] Some other processes besides absorption must account for the observed POA at atmospherically relevant concentrations.

**OBJECTIVE:** The objective of the proposed research is to identify the dominant partitioning mechanism for primary organic aerosol emitted from diesel-powered and gasoline-powered vehicles at atmospherically realistic concentrations in the range from < 5–30 µg/$m^3$. The results will provide input for regional airshed models that seek to predict changes to ambient organic aerosol concentrations in the presence of emissions control programs and/or climate change.

**DISCUSSION:** Task 1: POA emissions from diesel-powered and gasoline-powered motor vehicles will be diluted to concentrations ranging from < 5–50 µg/$m^3$. The influence of changing temperature on the aerosol will be investigated using a thermal

denuder system. Simultaneous measurements of gas-phase compounds will be made and related directly to the aerosol composition measurements. Dilution and heating can be used to independently adjust the final aerosol concentration and will determine to what extent these provide equivalent results with respect to the observed partitioning. The dilution system will be modified so that the relative humidity of the system can be manipulated. The RH will be adjusted between 50–80% to study the effects of aqueous partitioning. The secondary dilution system will be further modified so that black carbon (BC) particles produced from a separate burner can be introduced into the dilution air with a final concentration between 0–10 $\mu g/m^3$ to study the effect of adsorptive partitioning.

Major Task 2: The organic aerosol concentrations produced during each experiment will be measured as a function of dilution amount and thermodenuder temperature using a high-resolution Aerosol Mass Spectrometer capable of providing information about the size-resolved chemical composition of the particles and the elemental composition (i.e., ratios of carbon, hydrogen, oxygen and nitrogen) of the POA. Simultaneously, gas-phase concentrations and elemental compositions of carbonyls, alcohols, ketones and organic acids will be determined using a Time-of-Flight Chemical Ionization Mass Spectrometer and BC concentrations will be monitored using a multi-wavelength photoacoustic spectrometer.

Major Task 3: The gas and particle phase organic compounds will also be captured separately for offline analysis using a denuder-filter-PUF sampling train and analyzed using LC-MS for the concentration of individual organic compounds. Partitioning calculations that consider absorption into organic aerosol, aqueous partitioning, and adsorption onto elemental carbon will be used to identify the dominant processes at atmospherically relevant concentrations.

**BENEFITS:** The results of experiments conducted at atmospherically relevant concentrations will determine if the simple absorption theory can be extrapolated to the real atmosphere. These findings will have broad application within regional air quality models used to predict the efficiency of emissions control programs during State Implementation Plan (SIP) analysis. The results will strengthen the scientific basis for the emissions controls within the SIP.

**COST:** $300,000

**REFERENCES:**


1. A. P. Grieshop, M. A. Miracolo, N. M. Donahue, A. L. Robinson, Env Sci & Tech 43, 4750 (2009).
2. A. L. Robinson et al., Science 315, 1259 (Mar, 2007).
3. M. K. Shrivastava, E. M. Lipsky, C. O. Stanier, A. L. Robinson, Env Sci & Tech 40, 2671 (Apr, 2006).
4. J. R. Odum, T. P. W. Jungkamp, R. J. Griffin, R. C. Flagan, J. H. Seinfeld, Science 276, 96 (1997).
5. R. Volkamer et al., Geophysical Research Letters 33, (2006).
6. J. Chen, C. A. Jakober, S. Clegg, M. J. Kleeman, JAWMA submitted for publication, (2010).
7. C. A. Jakober et al., Environmental Science & Technology 42, 4697 (Jul, 2008).
8. M. J. Kleeman, S. G. Riddle, M. A. Robert, C. A. Jakober, Env Sci & Tech 42, 235 (Jan, 2008).
9. S. G. Riddle, M. A. Robert, C. A. Jakober, M. P. Hannigan, M. J. Kleeman, Environmental Science & Technology 41, 7464 (Nov, 2007).
10. M. A. Robert, S. VanBergen, M. J. Kleeman, C. A. Jakober, Journal of the Air & Waste Management Association 57, 1414 (Dec, 2007).

**TITLE: Quantification of ammonia slip from Selective Catalytic Reduction - equipped vehicles and estimation of secondary aerosol formation potential**

**PROBLEM:** Selective Catalytic Reduction (SCR) technology is becoming common for $NO_X$ emissions control for diesel vehicles. For SCR, ammonia (direct or through thermal decomposition of urea) is injected into the exhaust stream to promote a chemical reaction with $NO_X$ in the presence of a catalyst. Excess ammonia that does not react with $NO_X$ is called "ammonia slip," a source of ammonia emissions. Ammonia in the atmosphere is very reactive and causes the formation of ammonium sulfate ($(NH_4)_2SO_4$) and ammonium bisulfate ($NH_4HSO_4$). Ammonia slip also reacts with $NO_X$ to form ammonium nitrate if the SCR catalyst efficiency decreases after prolonged usage. Ammonia salt can cause downstream metal corrosion and promote PM formation. Atmospheric free ammonia, PM, and secondary organic aerosol (SOA) constitute a serious health and environmental hazard.

**PREVIOUS WORK:** Several in-house studies[1] form a basis for this research. Measurements of emissions from diesel cars equipped with urea injection SCR were made using an AVL SESAM FTIR system in early 2009. Preliminary results indicated ammonia concentrations in raw exhaust as high as approximately 100 ppm, as well as the presence of toxic gases such as hydrogen cyanide.

Related projects were undertaken to:

- determine the characteristics of the high Particulate Matter (PM) emitter, investigate the viability, cost-effectiveness, and potential benefits of professional repairs for emission reductions for the high PM emitters, and provide emission data of high PM emitters. These results can be used by ARB staff to develop emission estimates for inventory purposes for the present and the future;
- characterize the effect of sampling temperature on the production of primary particulate matter from year 2000 and newer model year light duty gasoline vehicles operated on winter-time and summer-time commercially available fuels;
- support efforts to improve the basic knowledge of how PM emissions are affected by future fuels, new vehicle technologies, sampling condition, variations in ambient temperature, humidity, and certain chemical compounds in the atmosphere that act as seeding agents for particle formation.

**OBJECTIVE:** This project will quantify the amount of amount slip emitted from two SCR-equipped vehicles operating at high, low, and transient modes; and investigate the correlation between ammonia slip and its effect on PM formation as well as PM mass emissions.

Major tasks include: 1) monitoring real-time exhaust gases concentrations; 2) monitoring real-time PM emission; 3) measuring real-time $NO_X$ emissions; 4) quantifying $NH_4^+$, $NO_3^-$, $SO_4^{2-}$ ion concentrations from collected PM; 5) investigating the relationship with additional PM formation relative to ammonia slip; 6) estimating the environmental impact from SCR $NO_X$ reduction technology.

[1] In-house projects 2R0601, 2R0805, 2R0903, and 2R0905.

**DISCUSSION:** Using ARB's Haagen-Smit Laboratory, Test Cells 2 and 3 offer:

- a 48" Chassis Dynamometer;
- a 10" Full Flow Dilution Tunnel;
- a Diluted Exhaust Emission Analysis Bench that can handle Bag Sampling for $CO_2$, THC, $CH_4$, CO, NO/ $NO_X$ , $N_2O$, and detailed HC analysis, as well as 1Hz Modal Sampling for $CO_2$, THC, CO, $NO_X$;
- AVL SESAM FTIR for real-time ammonia concentrations; and
- three independent, temperature-controlled particulate sampling units with secondary dilution capability. One of the sampling units can accommodate PUF filter cartridges for PAH sampling; real-time particulate sizer-Engine Exhaust Particle Sizer (EEPS).

Results will include PM and real-time ammonia emissions measurements from light diesel vehicle exhaust, combined with gaseous criteria pollutant measurements, gravimetric PM measurement, and filter ion analysis. These results will enable improved estimation and better understanding of how ammonia slip contributes to additional PM and SOA formation.

**BENEFITS:** Better understanding of the relationship between ammonia slip and PM formation will enable improved control of PM and SOA.

**COST:** $140,000 ($60k per vehicle procurement/purchase. $2k for fuel, $50k for equipment, 20k for repair and analysis). Cost can be significantly reduced if performed in-house.

**REFERENCES:**

1. Philip M. Fine, Constantinos Sioutas, Paul A Soloman (2008). "Secondary Particulate Matter in the United States: Insights from the Particulate Matter Supersites Program and Related Studies," *J. Air & Waste Manage. Assoc*. 58:234-253.

**TITLE: Development of innovative instrumentation to enable investigation of the relationship between $SO_2$ and sulfate**

**PROBLEM:** Reduction in particulate matter emissions from vehicles is a critical issue for meeting air quality improvement goals. Understanding the composition of particles is important to evaluate their health impacts as well as their formation mechanisms. Sulfur or sulfate is one of the major components of combustion and lubricant-derived particles. Sulfate levels in vehicle exhaust particulates can be readily measured, but it is important to understand the relative contribution between combustion and oil-derived particles and the conversion rates found for $SO_2$ to sulfate. With the low level of sulfur present in the fuel and oil products used in modern vehicles, detection limits in the part per billion (PPB) range are needed to measure the $SO_2$ contribution. Previous studies have shown a differential optical absorption spectrometer (DOAS) can be used successfully to make measurements at these levels from raw vehicle exhaust. The goal of this program will be to develop a DOAS and apply the technology to exhaust measurements from vehicles at the ARB Heavy Duty Emissions Test laboratory in Los Angeles.

**PREVIOUS WORK:** The Coordinating Research Council (CRC) [E-61 program] funded UCR to investigate the impact of sulfur content in the lubricating oil on four ultra-low-emission vehicles (ULEVs) and two super-ultra-low-emission vehicles (SULEVs), all with low mileage. Sulfur content in the lube oils ranged from 0.01% to 0.76% while the sulfur content of the gasoline was fixed at 0.2 ppmw. Vehicles were configured with aged catalysts and tested over the Federal Test Procedure (FTP), at idle, and at 50 miles per hour (mph) cruise conditions. In all testing modes, variations in sulfur level of the lubricant did not significantly affect the regulated gas-phase tailpipe emissions. In addition to the regulated gas-phase emissions, a key element of the research was measuring the engine-out sulfur dioxide ($SO_2$) in near real-time. This research used a methodology based on a differential optical absorption spectrometer (DOAS) to measure $SO_2$ from the lubricants used in this study. To provide near real-time, low-level measurement of engine-out $SO_2$, a differential optical absorption spectrometer (DOAS) was developed. This technique is commonly used for the measurement of $SO_2$ under low-level ambient conditions.

**OBJECTIVE:** The objective of this research is to construct, test and provide ARB a DOAS that can measure down to 10 ppbV in real time and evaluate $SO_2$ so a mass balance can be ascertained between $SO_2$ and sulfate, investigations would be done comparing the DOAS to integrated bags to see if there are any low level losses in bag samples. This would be a state of the art instrument. Training for ARB's technicians would also be provided as part of this program so they can run this instrument independently.

**DISCUSSION:** The DOAS measures the absorbance of ultraviolet (UV) light in the exhaust stream as it passes through an extractive sample cell with the sample gas filtered to remove PM. For the earlier work done on the CRC project, this sample cell was equipped with two quartz windows to allow the light to enter and exit a multi-pass mirror system White cell with a base length of 1.4 meters (m). To obtain the low detection limits needed for this project, optical path lengths of 14.0 meters were used. In this configuration, noise levels of 15 ppbv at one standard deviation were obtained. The

DOAS software was developed to determine the $SO_2$ concentration using a multi-dimensional least squares regression routine that removed interferences from molecules such as formaldehyde and $SO_2$. Operational tests with the instrument being used for a variety of $SO_2$ concentrations ranging from low to high sulfur oils, indicated that the DOAS readings were consistently within one standard deviation (15 ppbV) of the calibration gas value. For the CRC, study second-by-second $SO_2$ concentrations were obtained from the three-second DOAS readings using a linear interpolation. The concentrations were then converted into mass emissions rates by multiplying by the density of $SO_2$, and the time-aligned exhaust flow rate. The exhaust flow rate was determined on a second-by-second basis using the $CO_2$ tracer method.

For the proposed instrument, investigators will expand the pathlength so that detection limits of approximately 5 ppbV at 3 seconds integration time will be achievable. The DOAS will be made transportable so that it can measure either engine out or dilution tunnel values, as well as be simply moved to other labs within ARB. Faster response times are achievable and so are better detection limits, but this would require a very high flow sampling pump and a far more expensive White Cell to do this. UCR will develop the DOAS system for implementation in ARB's laboratories. The system will be developed and evaluated at UCR prior to installation in the ARB laboratory.

Once the instrument is completed, UCR will work with ARB on the installation of DOAS into one of its laboratories. UCR will work with ARB for a period of approximately 2 weeks, which will include on-site installation of the unit, verification and on-site calibration of the instrument, training, and an evaluation of the system on one test vehicle that will be provided by ARB. A brief manual will also be provided giving a description of the unit and simple instructions on how the instrument is operated.

**BENEFITS:** The benefits are that ARB would have an instrument with the capabilities to measure very low level $SO_2$. The instrument will be constructed so that it can measure $SO_2$ from both direct exhaust as well as from dilution tunnels. The instrument will be designed so ARB can transport it to other facilities in their system. The instrument will remain with ARB and training will be provided so ARB technicians will be able to use it independently.

**COST:** $90,000

**TITLE: Development of a high quality proportional gravimetric PM system for reliable in-use emissions measurements at low emissions rates**

**PROBLEM:** Particulate matter is known to cause adverse health effects. PM from diesel engines is classified as a Toxic Air Contaminant (TAC) by ARB. Regulations that have been implemented in 2007 require the use of diesel particulate filters (DPF) and provide significant reductions in PM levels. As PM emissions continue to be reduced, there is increasing interest in the measurement of PM in-use, by means of particle number, or with portable emissions measurement systems (PEMS). Unfortunately, these PM PEMS comparisons to gravimetric reference methods have proven to be unreliable where deviations are on the order of 100% and their measurements are dramatically dependent on composition, particle size and concentration. The real time instruments are not faulty, but their measurement principles do not correlation with the gravimetric method, where a combination of size, shape, composition, and chemistry contributions vary, causing the poor correlation. The focus of this research will be on the development and evaluation of a high quality gravimetric proportional PM measurement system designed for in-use conditions based on the reference method.

**PREVIOUS WORK:** ARB, in conjunction with the University of California at Riverside CE-CERT (Bourns College of Engineering Center for Environmental Research and Technology), has ongoing programs in the areas of in-use PM measurement using both number and gravimetric methods. CE-CERT has conducted a preliminary evaluation of the PMP methodology using CE-CERT's Mobile Emissions Laboratory (MEL) and with testing at ARB's heavy-duty chassis laboratory in Los Angeles. CE-CERT has also recently completed the PM PEMS measurement allowance program were UCR's MEL was an integral part of the allowance determination. The PM PEMS MA program evaluated the state of the art PM PEMS that were designed specifically for in-use conditions while correlating with the gravimetric reference method. These PM PEMS measurement techniques did not perform well and have shown to have measurement errors on the order of 100% at the proposed in-use thresholds of 0.03 g/hp-h.

**OBJECTIVE:** The objective of this research is to develop and evaluate a new gravimetrically based system designed specifically for in-use conditions including on-highway, marine, and non-road applications. The evaluation will include both laboratory-based and on-road measurements in comparison with UCR's MEL gravimetric reference method.

**DISCUSSION:** The development of a reliable in-use gravimetric PM system will be based on the latest regulations in Title 40 Part 1065, with consideration for possible changes to Part 1065 such as dilution air set points and residence times. The goal of the system is to sample a proportional amount of exhaust and sample that diluted exhaust onto a gravimetric filter with a system consistence with Part 1065 specifications. The technology for proportional sampling and loading a filter is established, but has not been suitably packaged for in-use conditions. In addition, in-use testing requires autonomous control which will be implemented using a work-based window approach where a maximum of 24 filters can automatically be sequenced into the system. The controls will be designed to be remotely controlled and a final product that will be reproducible for ARB scientists and investigators.

The system will be evaluated and compared against UCR's MEL on UCR's dynomometer, then on UCR's chassis dynomometer, then final deployment on a 2007 or newer diesel vehicle with a bypass system to evaluate the ability to detect various conditions of DPF status.

In order to perform proportional sampling, an exhaust flow meter is needed. CE-CERT will use its experience in flow measurement and integrated a design between flow and sampling for the gravimetric system design. During development of the system, specific details about portability and robustness will be considered, while archiving optimizing dilution and PM sampling methods.

**BENEFITS:** The development of a reliable, in-use gravimetric PM system is necessary to quantify and understand in-use emissions inventories for on-highway, non-road and marine applications. The results from this program can be used to help improve emission inventories, our PM models and thus provide needed information to suggest new legislation for continued improved air quality. Current regulations require the measurement of PM in-use, but the tools being used do not necessarily measure all parts of the PM and will not be reliable for inventory purposes. This project will provide the necessary tools to accurately quantify the emissions from California's in-use fleets.

**COST:** $300,000

**TITLE: Extended analysis of the CARES aerosol chemistry data to characterize the sources and processes of organic fine particulate matter**

**PROBLEM:** Organic aerosol (OA) represents a major mass fraction of fine particles in California and in many regions globally. But the emission sources, formation mechanisms, and evolution processes of atmospheric OA remain poorly characterized. This knowledge gap limits the ability of current models to simulate ambient OA concentrations and properties. In particular, there is critical need to improve the description of the mechanisms of secondary OA formation in models.

Because the results from model predictions usually guide emission control strategies, an improved understanding of OA pollution is important to developing effective regulatory policies on air quality. This is directly relevant to California since over the years the state's emission control programs have not reduced OA loading as rapidly as the reductions in inorganic particulates and black carbon. That means further fine particle control may need to focus on OA.

Evaluation and improvement of models require data-driven phenomenological PM descriptions. Real time, quantitative, and size-resolved measurement on ambient aerosol composition (e.g., with Aerosol Mass Spectrometers) is the key to this critical need. These measurements, however, were rare in California. Furthermore, while advanced analysis is essential to exploring the rich information contents of fast compositional measurement data, so far it has not been done in Northern California. The U.S. Department of Energy (DOE) funded Carbonaceous Aerosols and Radiative Effects Study (CARES) in the Sacramento area in 2010 will yield sophisticated ambient aerosol measurement data, of which detailed analyses will provide valuable insights into sources and processes of OA in the Sacramento and foothills region.

**PREVIOUS WORK:** The Aerodyne Aerosol Mass Spectrometers (AMS) provide real-time, quantitative, and size-resolved data on submicron particulate (PM1) species (e.g., sulfate, nitrate, ammonium, chloride, and organics) with fast time resolution.[1] Numerous field campaigns have proven AMS as a powerful tool for characterizing the properties and lifecycle of atmospheric fine PM.[2, 3]

The new High-Resolution Time-of-Flight AMS (HR-ToF-AMS) has a high mass resolution of ~ 5000 – 6000.[4] It allows the determination of the elemental ratios (O/C, N/C, etc) of OA materials,[5] based on which insights into particle sources and processes may be gained. For instance, the O/C ratio could be used as a key indicator for aerosol aging.

Coupled with a temperature-controlled thermodenuder (TD), the AMS can also provide information about volatility of individual species.[6] This information is critically important to understanding aerosol growth and lifetime.[7]

Multivariate statistical analysis of the AMS data has broadened the field of OA source appointment. These analyses deconvolve the total sub-micron OA mass into contributions from several OA types associated with distinctive sources and processes (e.g., primary, secondary, biogenic, biomass burning, etc) [Zhang et al., 2005; Zhang et

al., 2007; Lanz et al., 2007; Ulbrich et al., 2009]. This lumped classification of the total organic mass may offer a simple parameterized representation of the complex OA appropriate for model evaluations and developments.

**OBJECTIVE:** Investigators will be funded by DOE to deploy a TD–AMS/SMPS system during CARES and to perform initial analysis to determine the concentration, size distribution, and volatility of aerosol species.

ARB funding will support advanced analyses to characterize the sources, formation, and atmospheric evolution of OA in the Sacramento and foothills region. Specific objectives are to:

1) Determine the elemental composition of OA.
2) Classify OA mass into source- and process-specific types, focusing on unraveling the influences from primary vs. secondary and urban vs. biogenic emissions.
3) Investigate the photochemical processing and evolution of aerosol pollutants in urban plumes and in mixtures of biogenic and urban emissions.
4) Collaborate with atmospheric modelers at ARB to use research results to improve and validate models.

**DISCUSSION:** Investigators will be funded by DOE to deploy in parallel an HR-ToF-AMS and a Scanning Mobility Particle Sizer (SMPS) after a temperature-stepping thermodenuder at Cool (the T1 site of CARES; http://acrf-campaign.arm.gov/cares) during the CalNex study period. DOE will also support the initial analyses of the TD–AMS/SMPS dataset, from which will be determined: 1) The size-resolved chemical composition of particles; 2) The temporal variations (at minutes resolution) of sulfate, nitrate, ammonium, chloride, and total organics and their size distributions; and 3) The volatility profiles of these species.

ARB funding will enable investigators to conduct further, advanced analysis to this TD-AMS/SMPS dataset and collaborate with ARB's atmospheric modelers. Research will focus on the organic content of the aerosols. Investigators will first analyze the high resolution mass spectra (HRMS) to determine the elemental compositions of OA, then perform multivariate analyses to the HRMS, chemically-resolved size distributions, and volatility profiles. Investigators will deconvolute and determine distinct OA types, which will be related to different sources and processes based on extensive examinations on their correlations with tracer compounds and other parameters.

Investigators will probe photochemical processing and evolution of OA properties characteristic to the Sacramento area via integrated analyses and focused case studies. Backtrajectory or FLEXPART analyses will be performed to examine plume sources. Photochemical behavior of air-masses will be inferred using VOC oxidation clock and AMS internal indictors such as O/C ratio.

The study will also compare the results from this research to information available from simultaneous AMS measurements to be performed at three other ground sites (i.e., downtown Sacramento, LA, and Bakersfield), two aircraft platforms (DOE and NOAA), and a ship platform (NOAA).

Finally, investigators will collaborate with atmospheric modelers at ARB to incorporate, compare, and otherwise make use of as much of the detailed study results as possible.

**BENEFITS:** This research will provide useful new data on organic carbonaceous PM in the Sacramento and Sierra foothills of California. Quantitative time trends, size distributions and temperature-dependent volatility profiles of multiple primary and secondary OA (i.e., POA and SOA) components in submicron particles will be obtained. From these data, important insights may be gained on the relative source strength of POA, the mechanisms leading to SOA formation, and the photochemical processing of particulate organics in Northern California. These results may be compared directly to findings from the South Coast Air Basin, the San Joaquin Valley, and mobile platforms where similar measurements will be made during CalNex. These comparisons will lead to a better understanding of regional differences in OA characteristics, sources, and effects within California. Also importantly, since these data represent a self-consistent observation-based PM description, they will have broad application within regional air quality models used to predict the efficiency of emissions control programs. In summary, the results from this research will be of immediate value for developing air quality attainment strategies in California.

**CO-FUNDING:** The Atmospheric System Research (ASR) Program of DOE will fund the deployment of the Thermodenuder – HR-ToF-AMS & SMPS system at the Cool site (i.e., the T1 site downwind of urban Sacramento) of the CARES campaign. The ASR will also provide three months of funding for the initial analysis of the TD-AMS/SMPS dataset. The cost of this project is much reduced because of the DOE funding.

**COST:** $155,000

**REFERENCES:**


1. Canagaratna, M., J. Jayne, et al. (2007), Chemical and Microphysical Characterization of Ambient Aerosols with the Aerodyne Aerosol Mass Spectrometer, Mass Spectrometry Reviews, 26, 185-222, DOI 110.1002/mas.20115.
2. Zhang, Q., J. L. Jimenez, et al. (2007), Ubiquity and Dominance of Oxygenated Species in Organic Aerosols in Anthropogenically-Influenced Northern Hemisphere Mid-latitudes, Geophys. Res. Lett., 34, L13801, doi:10.1029/2007GL029979.
3. Jimenez, J. L., M. R. Canagaratna, et al. (2009), Evolution of Organic Aerosols in the Atmosphere, Science, 326, 1525-1529, DOI: 1510.1126/science.1180353.
4. DeCarlo, P. F., J. R. Kimmel, et al. (2006), A Field-Deployable High-Resolution Time-of-Flight Aerosol Mass Spectrometer, Analytical chemistry, 10.1021/ac061249n.
5. Aiken, A. C., P. F. DeCarlo, et al. (2008), O/C and OM/OC Ratios of Primary, Secondary, and Ambient Organic Aerosols with a High Resolution Time-of-Flight Aerosol Mass Spectrometer, Environ. Sci. and Technol., 10.1021/es703009q.
6. Huffman, J. A., K. S. Docherty, et al. (2009), Chemically-resolved aerosol volatility measurements from two megacity field studies, Atmospheric Chemistry and Physics, 9(18), 7161-7182.
7. Robinson, A. L., N. M. Donahue, et al. (2007), Rethinking Organic Aerosols: Semivolatile Emissions and Photochemical Aging, Science, 315, 1259, DOI: 1210.1126/science.1133061.
8. Lanz, V. A., M. R. Alfarra, et al. (2007), Source apportionment of submicron organic aerosols at an urban site by factor analytical modelling of aerosol mass spectra, Atmos. Chem. Phys., 7, 1503-1522.
9. Ulbrich, I., M. Canagratna, Q. Zhang, D. Worsnop, and J. L. Jimenez (2009), Interpretation of Organic Components from Positive Matrix Factorization of Aerosol Mass Spectrometric Data, Atmos. Chem. Phys., 9, 2891-2918.

10. Zhang, Q., M. R. Alfarra, et al. (2005), Deconvolution and quantification of hydrocarbon-like and oxygenated organic aerosols based on aerosol mass spectrometry, Environmental Science & Technology, 39(13), 4938-4952, doi:4910.1021/es048568l.

**TITLE: Methane Emissions Source Apportionment Using Stable Isotopes**

**PROBLEM:** Methane ($CH_4$) is emitted both naturally and through human activities. The global mixing ratio of $CH_4$ in the atmosphere has more than doubled since the pre-industrial period, rising from around 750 parts per billion (ppb) in 1800 to the current level of around 1770 ppb. With a global warming potential is 25 times that of carbon dioxide ($CO_2$) methane is second only to carbon dioxide as a greenhouse gas responsible for enhanced climate forcing between the pre-industrial era and the present.

As required by the AB 32, ARB developed a statewide GHG emissions inventory that provides estimates of the amount of GHGs released into the atmosphere by human activities annually within California. In addition to developing and verifying the statewide GHG emissions inventory, AB 32 also requires ARB to adopt a reduction plan of GHG emissions to 1990 levels by 2020. Researchers have recommended that controlling $CH_4$ emissions a cost-effective solution for reducing GHG emissions. Therefore, a verified $CH_4$ emissions inventory with accurate source information is critical for ARB to develop well-designed mitigation plans.

**PREVIOUS WORK:** Stable isotope information provides useful information on $CH_4$ sources and sink processes.[1,2] Stevens and Rust[3] (1982) first proposed that a mass-weighted stable carbon isotopic balance between $CH_4$ sources and sink processes and the $\delta^{13}CH_4$ value in the atmosphere would help define the $CH_4$ budget. Air samples measured for $\delta^{12}C$ and $\delta^{13}C$ values of $CH_4$ as well as $CH_4$ mixing ratio can be used to help in determining $CH_4$ source apportionment.

Tyler et al[4] (2009) demonstrated the effectiveness of using the above approach to study $CH_4$ source apportionment in the Los Angeles Basin. Individual point sources of $CH_4$ such as dairy farms, oil wells, oil refineries, landfills, car traffic, and sewage treatment plants were measured to characterize their $CH_4$ $\delta^{12}C$ and $\delta^{13}C$ compositions. In addition, integrated whole air samples were collected from various regions in the Los Angeles basin. Preliminary results indicate that Los Angeles air is dominated with thermogenic emission sources which are similar to natural gas isotopic signatures from oil extraction field and refinery emissions.

**OBJECTIVE:** The objective of this proposal is to provide critical $CH_4$ isotopic information from emission sources and at existing $CH_4$ monitoring network stations for source apportionment purpose. The expected results are essential to verify ARB's GHG emissions inventory. In addition, long-term records of $CH_4$ isotopic signatures are extremely valuable for monitoring changes of $CH_4$ emissions and evaluating the effectiveness of California's efforts to reduce $CH_4$ emissions. This study can also help identify possible un-inventoried sources.

**DISCUSSION:** The proposed work can be divided into four major tasks:

Task 1. Purchasing a cavity enhanced laser $CH_4$ isotope analyzer. As of recently, there are reliable instruments available commercially to measure $\delta^{12}C$ and $\delta^{13}C$ values of $CH_4$ in real time. These laser analyzers accurately generate a data point every few seconds which provides essential source isotopic information -- as opposed to the traditional gas

chromatography (GC) method which requires collecting samples in vials or canisters, transporting them back to the laboratory, followed by cryogenic pre-concentration and cryo-focusing, and then analyzing them with an expensive isotope ratio mass spectrometer.[5,6] The traditional GC method is labor-intensive and expensive. With this proposed laser analyzer, one can measure essentially unlimited number of samples with significantly less instrumentation cost and maintenance expenditures. Note that the $CH_4$ analyzers currently installed at the $CH_4$ monitoring network stations are still the best choice for their accuracy and stability. However, those $CH_4$ analyzers measure total $CH_4$ mixing ratio without the isotopic composition information which is needed to further study contributing sources.

Task 2. Establish a $CH_4$ isotopic signatures library. The accurate method of characterizing source isotopic signatures is to apply so-called "Keeling Plot algorithm" with lots of isotopic data points measured from an emission source. The proposed laser $CH_4$ isotope analyzer is well designed for this task. It will be deployed at or near emission sources (e.g., landfills, natural gas production facilities, wastewater treatment plants, wetlands, dairies, rice paddies, etc). A $CH_4$ isotope library which includes $\delta^{12}C$ and $\delta^{13}C$ values will be established cost effectively.

Task 3. Stationary $CH_4$ isotope measurements. The same proposed laser $CH_4$ isotope analyzer will be rotated amongst existing $CH_4$ monitoring network stations for an extended period of time (e.g., weeks). The measured $\delta^{12}C$ and $\delta^{13}C$ values, along with wind direction and wind trajectories, will be studied and compared with those collected from $CH_4$ emission sources to characterize source sectors. This source contribution information will be compared with CARB's $CH_4$ emissions inventory which is available by source sectors. The studied results will also provide essential emissions message to the ongoing $CH_4$ inverse modeling project.

Task 4. Long term $CH_4$ isotope measurements. Long term measurements of $CH_4$ isotopes will continuously monitor isotopic compositions for seasonal variations and changes in emission activities.

**BENEFITS:** This project will enhance ARB's $CH_4$ monitoring network by using stable isotopes of $CH_4$ to differentiate emission sources, thereby facilitating source apportionment and providing critical data to verify $CH_4$ emissions inventory in California which is required by AB32. Effective GHG reduction strategies rely largely on accurate GHG emissions inventory. Research results will help prioritize, achieve, and verify $CH_4$ emissions reductions.

**COST:** $128,000

## REFERENCES


1. Tyler, S. C., A. L. Rice, and H. O. Ajie, Stable isotope ratios in atmospheric $CH_4$: Implications for seasonal sources and sinks, *J. Geophys. Res.,* 112*,* D03303, doi:10.1029/2006JD007231, 2007.
2. Turnbull, J., A. Karion, C. Sweeney, P. Tans, B. Miller, J. Miller, S. Montzka, M. Fischer, I. Faloona, T Guilderson, S. Lehman, Measurement of fossil fuel derived carbon dioxide and other anthropogenic trace gases above Sacramento, California in Spring 2009, http://www.esrl.noaa.gov/gmd/annualconference/pdfs/6-Turnbull.pdf

3. Stevens, C.M. and Rust, F.E., The carbon isotopic composition of atmospheric methane, Journal of Geophysical Research, vol. 87, June 20, 1982, p. 4879-4882.
4. Tyler et al., 2009, Isotopic Constraints on Sources of Methane in Los Angeles, CA, poster presentation at American Geophysical Union 2009 Fall meeting.
5. Craig, H., Isotopic standards for carbon and oxygen and correction factors for mass-spectrometric analysis of carbon dioxide, *Geochim. Cosmochim. Acta,* 12, 133-149, 1957.
6. Rice, A. L., A. A. Gotoh, H. O. Ajie, and S. C. Tyler, High precision continuous flow measurement of $\delta^{13}C$ and δD of atmospheric $CH_4$, *Anal. Chem.*, 73, 4104-4110, 2001.

**TITLE: Improving California's GHG emission inventory through ground-referenced remote sensing of fossil fuel industry emissions, and biological methane and carbon dioxide emissions**

**PROBLEM:** Meeting legislatively mandated greenhouse gas (GHG) emission targets requires accurate knowledge of GHG budgets and good decisions regarding where to focus scarce resources. Although policy has focused mostly on carbon dioxide ($CO_2$), methane's ($CH_4$) lifetime radiative impact is significant, approximately 30% of $CO_2$ at current concentrations. Its far shorter atmospheric residence time suggests methane regulation can be more economically efficient than regulating $CO_2$.[1]

Methane exhibits strong spatial variations, as well as strong diurnal and seasonal variability. These heterogeneities have been characterized by small-scale studies in select cases, but many remain uncharacterized. Spatio-temporal variability presents a significant challenge for scaling from local site and time-specific GHG measurements (e.g., ARCTAS or field sensors) to annual statewide GHG budgets. Also, discrepancies between top-down (or atmospheric inversion) and bottom up (inventory) approaches for methane budget estimation suggest significant inventory emission underestimation.[2]

Fossil Fuel Industry (FFI) emissions are the primary anthropogenic source of ancient carbon (besides combustion), while they represent the largest non-anthropogenic US $CH_4$ source, slightly larger than landfills;[3] yet uncertainties are three-fold. Despite their importance, a thorough literature search revealed only a couple of peer reviewed, published measurements studies in recent decades,[4,5] as opposed to inventory approaches.[6, 7]

Investigators will evaluate temporal and spatial variability in $CH_4$ emissions using the GOSAT satellite sensor in combination with targeted field measurements, and complimentary remote observations from MODIS (Moderate Resolution Imaging Spectrometer) and AVIRIS (Airborne Visible Infrared Imaging Spectrometer). Researchers will also derive improved emission estimate for FFI emissions from key terrestrial and marine production facilities and refineries using a combination of repeat remote sensing and ground-reference measurements.

**PREVIOUS WORK:** AVIRIS data analysis has mapped $CH_4$ plumes from marine seeps using radiative transfer calculations[8] and spectral band ratios,[9] an imaging spectrometer first. Preliminary analysis of AVIRIS data for rice paddies shows strong $CH_4$ signatures. AVIRIS and ground-reference data are being analyzed in conjunction with contemporaneous ARCTAS/CARB data. AVIRIS data for Platform Holly captured $CH_4$ flaring during five overflights and is being analyzed. Analysis of SeBASS (Aerospace Corporation's hyperspectral, thermal imaging spectrometer) data mapped $CH_4$, $CO_2$, and trace gas plumes from terrestrial and marine sources, including refineries and power plants, and captured the atmospheric plumes' extreme heterogeneity, a key imaging spectrometer advantage.

Temporal emission trends were identified from two decades of West Campus Station THC data for geologic seep field emissions on diurnal, seasonal, and decadal scales.[10] Analysis shows strong, storm-driven emission modulation.[11]

Investigators have developed a field gas chromatograph (GC) four-channel, flame ion detector for $CH_4$, $CO_2$ and CO (by methanizer), and higher n-alkane for small mobile platform (boat, truck) measurement in hostile environments (sea spray) with internal air, hydrogen, and calibration gases with THC at 2 Hz and $CH_4$ speciation at 0.04 Hz. THC and $CH_4$ speciation accuracy is ~40 and ~20 ppb, respectively.

Satellite GOSAT $xCH_4$ data analysis is starting for geologic marine emissions and for SCIAMACHY data, $CH_4$ emission are being analyzed in collaboration with Bremen IUP (Germany), and show high correlation between anomalously high, regional $CH_4$ columns and FFI production. These preliminary analyses justified (NSF supported) vicarious collection of Gulf of Mexico platform observations during AVIRIS operations in response to the Gulf Oil Spill. The MODIS active fire product data has been used to validate fire danger indices[12] and to estimate fire temperature and area, which modify emission efficiency.[13]

**OBJECTIVE:** The objective is to investigate the seasonal and diurnal variability of a range of important biological GHG emission sources, particularly, rice paddies, forest fires, coastal wetlands, shallow lakes or reservoirs, and FFI facilities, using a combination of GOSAT GHG satellite data, ground-reference measurements (GC and fixed stations), and AVIRIS and MODIS data. For FFI emissions, we will derive an improved emission estimate from key marine and terrestrial production sources including refineries by repeat remote sensing and ground reference measurements.

This study leverages the successful NASA-funded approach that pioneered mapping $CH_4$ with AVIRIS for natural marine (low-albedo surface) geologic $CH_4$ emissions,[8] and Aerospace Corporation experience mapping methane emissions with the SeBASS sensor. To reduce costs we will seek to combine with other NASA projects to share AVIRIS launch costs, including data from calibration flights (courtesy of collaboration with JPL), or through collaboration with a JPL Ventures project to measure $CH_4$ spectroscopically, or from existing AVIRIS data. Methane will be mapped directly from AVIRIS data, while MODIS data will allow evaluation of the relationship between MODIS-derived measures of rice productivity (from measures such as the Normalized Difference Vegetation Index) and GOSAT-derived GHG budgets. The MODIS active fire product will be used to evaluate the relationship between GHG emissions and active fires. This will dramatically improve annual California GHG budgets by improving scaling of disparate ground-based sensor measurements, such as the California GHG monitoring network, to a statewide basis. Further improvements in inventories will result from including seasonal variations based on satellite data. Scaling FFI methane emissions will be based on California facility data and compared with SCIAMACHY and GOSAT $CH_4$ products.

**DISCUSSION:** Our approach is nested (satellite, GOSAT–10x10km pixels; aerial, AVIRIS; surface ground-reference measurements). We will collect and analyze GOSAT and SCIAMACHY (historical) $CH_4$ column-abundances for important California $CH_4$ sources: FFI emissions, fires, rice paddies, wetland emissions, and shallow water reservoirs on a regional (e.g., Sacramento basin) and statewide basis and for ground-reference sites. GOSAT $CH_4$ column-abundances will be compared for California rice growing areas and wetland areas with MODIS NDVI data of plant productivity and biomass. Studies show the two are correlated, although underlying processes

(temperature, microbial activity, plant productivity, etc) likely are important. MODIS fire data also will be related to $CH_4$ emissions. Here, biomass buildup provides available fuel for fires and $CH_4$ emissions. Satellite data will allow assessment of temporal (annual estimate) emissions.

AVIRIS reference data will be used to reference GOSAT and MODIS satellite data, timed to coincide with GOSAT overpasses for optimum time in terms of illumination (solstice), and weather (low cloud cover probability), i.e., towards mid-summer, and emissions from seasonally varying sources like agriculture and fires. A single ER2 AVIRIS flight can cover all sites in one day; however, costs are high if not requested within NASA. We are endeavoring to secure support through JPL collaborations by providing local, California-based ground reference data. Data analysis will use the methods of Roberts[8] and Bradley[10] modified to terrestrial (heterogeneous) surfaces.

Airborne data will be ground referenced with coordinated measurements from fixed (air pollution stations) and mobile (boat, plane, truck) platforms, coordinated with aerial overflights to characterize $CH_4$ plumes including aerial *in situ* sampling (during SeBASS flights). Then, emissions are derived from plume modeling,[14] while relative facility emissions can be inferred directly from retrieved $CH_4$ column abundances. Where accessible, air pollution station data analysis will be used to derive annual emissions and identify temporal trends.[10]

California study sites leverage proximity to Edwards AFB, UCSB, offshore facilities, and Aerosopace Corporation. AVIRIS has overflown offshore SB Channel platforms–$1x10^6$ barrel $day^{-1}$; flights are needed for the Elk Hills Field (2387 wells, $7x10^4$ barrel $day^{-1}$) and other oil fields in the Bakersfield area. Here, ARCTAS measured the highest $CH_4$ levels anywhere in California. These levels could relate to enhanced emissions through natural migration pathways due to re-injection, which spatial mapping could reveal.

*Method application* will focus on quantifying approach limitations with respect to detection limits by radiative transfer modeling (e.g., Roberts[8]), statistical analysis of variability between facility emissions, and comparison with bottom-up emission budgets.

**BENEFITS:** The primary study benefits are improved estimates of important biological and geological $CH_4$ source emissions, from FFI, fires, rice paddies, wetland emissions, and shallow water reservoirs. FFI is the largest anthropogenic $CH_4$ source, yet emissions estimates largely remain unvalidated. Data analysis will identify the most economically efficient mitigation targets, enabling more effective regulatory mitigation strategies.

Biological source uncertainties are large and highly variable, seasonally and interannually. Relating these source emissions to MODIS data will improve statewide inventories, which are based on scaling from local to statewide emissions. Further, through connection to GOSAT methane data, the discrepancy between top-down and bottom-up estimates on a statewide basis can be reduced for these important sources.

Anticipated publications from this research (PIs have a proven publication track record) will be an important benefit given the near absence of peer-reviewed literature on FFI $CH_4$ emissions and the paucity of studies on other biological sources. Finally, we will

further refine remote sensing techniques developed for the relatively spectrally homogeneous sea surface to terrestrial sources.

**CO-FUNDING:** A NASA proposal is under consideration to identify Gulf of Mexico FFI emissions by remote sensing and ground reference measurements ($400k). Benefits arise from a NASA AVIRIS project (Leifer $589) to remote sense and ground-reference $CH_4$, and a University of Utah subcontract (Roberts $296K) to develop hyperspectral indices for estimating fire temperatures and mapping methane. Leifer and Roberts are GOSAT Research Associates, providing access to GOSAT data that are not publicly available. Leifer also is PI for the first NASA Gulf Oil Spill Airborne Response for data collection (~487.5k), and has collected extensive platform data. Further, a NSF RAPID (200k) study is funded to analyze the GOM platform data and collect *in situ* samples.

**COST:** $350,000

**REFERENCES:**


1. Shindell et al (2005) An emissions-based view of climate forcing by methane and tropospheric ozone. *Geophys Res Lett* 32 L04803.
2. Hsu et al (2010) Methane emissions inventory verification in Southern California. *Atm Environ* 44(1) 1-7.
3. EPA (2009) US Greenhouse Gas Inventory Reports
4. Shorter et al (1996) Methane emission measurements in urban areas in Eastern Germany. *J Atmos Chem* 24(2) 121-140.
5. Villasenor et al (2003) An air quality emission inventory of offshore operations for the exploration and production of petroleum by the Mexican oil industry. *Atmos Environ* 37(26) 3713-3729.
6. Subak (1999) On evaluating accuracy of national methane inventories. *Environ Sci & Policy* 2(3**)** 229-240.
7. Kirchgessner et al (1997) Estimate of methane emissions from the U.S. natural gas industry. *Chemosphere* 35(6) 1365-1390
8. Roberts et al (2010) Mapping methane emissions from a marine geological seep source using imaging spectrometry. *Remote Sensing Environ* 114(3) 592-606
9. Bradley, Leifer, Roberts (2009) Atmospheric long-term monitoring of temporal trends in seep field emissions. *Atm Env*, *In Press.*
10. Bradley, Leifer, Roberts, et al (2010) Remote sensing of marine methane emission with the Airborne Visual Infrared Imaging Spectrometer by band ratios. *Nature Geosci*, *in prep.*
11. Leifer et al (2010a). Airborne observations of a massive methane plume from the Coal Oil Point seep field. *Atmos Environ, in prep*

11a. Leifer et al (2010b) The storm impact on seep methane benthic-atmospheric fluxes: The importance of wind history. Atmos Environ*, in prep.*

12. Schneider, Roberts, Kyriakidis (2008) A VARI-based relative greenness from MODIS data for computing the Fire Potential Index. *Remote Sensing Environ* 112, 1151-1167.
13. Eckmann, Roberts, Still (2008) Using multiple endmember spectral mixture analysis to retrieve subpixel fire properties from MODIS. *Remote Sens Environ* 112(10) 3773-3783.
14. Leifer, Roberts, Margolis, Kinnaman (2006) In situ sensing of methane emissions from natural marine hydrocarbon seeps: A potential remote sensing technology. *Earth Plan Sci Lett* 245(3-4) 509-522.
15. Walker (1961) Water Injection Program, shallow oil zone, Elk Hills Field, California, SPE Regional Meeting, SPE, pp 7.
16. Yu, Ezekwe (1998) Gas Management Models for Optimization of Elk Hills Gas Strategies, SPE Gas Technology Symposium, SPE, pp 12.

**TITLE: Synthesis of policy-relevant findings from the CalNex 2010 field study**

**PROBLEM:** The field phase of the joint ARB-NOAA CalNex 2010 field study (see Study Overviews referenced below) was completed during the summer of 2010. It is important to now ensure that the results of that study are made fully available to California policy makers who must deal with air quality and climate change issues. The fieldwork was planned to address twelve Science Questions (see the CalNex White Paper referenced below for a listing of these questions) that were formulated to guide the study planning. The questions address many specific and general science needs that are required to improve policy responses to air quality and climate change issues. They address emissions (both greenhouse gases and ozone and aerosol precursors), important atmospheric transformation and climate processes, and transport and meteorology. Instrumentation and platforms were deployed to collect the data sets necessary to address these questions. Analysis of the resulting data sets will lead to a great many science publications during the coming years. However, these publications are intended to present interesting scientific findings, but will not necessarily directly address the Science Questions. *As fully as possible the findings from these publications and from other needed analysis must be synthesized in a timely fashion and in a form most useful to policy makers. Completing that synthesis is the problem to be addressed by this work.*

**PREVIOUS WORK:** Preliminary data sets from the completed CalNex 2010 fieldwork have been prepared, for the most part while the field deployments were underway. Presently, measurement results are being subjected to quality assurance/quality control procedures, and the final data archives are being prepared. Individual scientists are formulating the analyses that they find exciting and intend to follow through to scientific publications. ARB's contracts for data collection also funded data analysis by the Principle Investigators and NOAA has plans for a significant data analysis effort.

**OBJECTIVE:** The goal of the proposed work is to bring the results of the ongoing CalNex 2010 analysis together to answer the twelve Science Questions as fully as possible, in a timely fashion and in a form most useful to policy makers.

**DISCUSSION:** The proposed work can be divided into three major parts:

1) ***Coordination and integration of ongoing analyses*** being conducted by separate scientists with a diverse range of interests. The results of these analyses will be presented at a variety of forums, and published in a variety of journals. A coherent synthesis of these results as they pertain to the Science Questions in a single location will greatly benefit policy makers. This synthesis will comprise a whole that is significantly greater than the sum of the individual analyses.
2) ***Identification and performance of additional needed analysis***. It is very likely that some aspects of the Science Questions will not be directly addressed by the spontaneous analyses conducted by individual scientists. Such "holes" will be identified and filled with additional analysis to the extent that resources allow.
3) ***Interaction with California regional air quality modelers.*** The CalNex 2010 data set will provide an unprecedented wealth of data to which model simulations can be compared. In previous field studies we have found that close interaction

between the measurement people and the modelers significantly improves the ultimate scientific as well as policy relevant information that finally emerges. One goal of the proposed work is to facilitate one-on-one and small group interactions between these two, often disconnected, groups of workers.

The work outlined in the above three parts could be a very resource intensive process. Support requested here is relatively modest, and close attention will be paid to prioritizing the effort in order to maximize the return from this support.

**BENEFITS:** The state of California (as well as the federal government) has made a substantial investment in conducting the field measurement phase of the CalNex 2010 field study. A very wide range of scientific findings based upon the resulting data sets will be published in the coming years. The work proposed here will maximize the policy relevant information that can result from these findings, and will present that information in a timely fashion and in a form most useful to policy makers. The availability of this information will provide the basis for improving the effectiveness and the efficiency of California air quality and climate change policies.

**COST:** $250,000

**CO-FUNDING:** Several hundred scientists in the federal, state and university systems have been involved in the measurement phase of CalNex, and generally all are supported through various channels to participate in the ongoing data analysis and presentation of results. The work proposed here is designed to leverage this very large investment to maximize the relevant information that can be conveyed to the California policy community as efficiently as possible.

**REFERENCES:**

CalNex White Paper, http://www.arb.ca.gov/research/calnex2010/calnexus_white_paper_01_09.pdf
NOAA CalNex Science and Implementation Plan, http://esrl.noaa.gov/csd/calnex/scienceplan.pdf
Study overviews, http://www.arb.ca.gov/research/calnex2010/calnex2010.htm and
http://esrl.noaa.gov/csd/calnex/

## APPENDIX C: Concepts Recommended for Climate Change, Energy Efficiency and Conservation

### Table of Contents

**TITLE: Developing databases to estimate California-specific climate forcing benefits of "cool roofs"**

**PROBLEM:** Recognition of the potentially devastating environmental impact of uncontrolled emissions of greenhouse gases (GHGs) led to passage of the Global Warming Solutions Act in 2006 which committed California to cap and then reduce emissions of anthropogenic GHGs to 1990 levels by 2020. "Cool roofs" - roofs which reflect a larger potion of the sun's radiation than conventional roof materials - are recognized to decrease air conditioning load, thereby saving electricity and the associated $CO_2$ emissions. In addition to energy savings, modifications that increase roof reflectivity (albedo) also produce a climate "benefit" by creating a negative radiative forcing proportional to the amount of additional sunlight reflected back through the atmosphere to space, compared to the preexisting surface. The magnitude of this benefit for any particular building or community depends on the marginal increase in albedo achieved by changing or coating roofing material, the total area of roof converted, and the amount of sunlight at the building site(s). The effect of albedo change on radiative forcing, and thus the magnitude of the benefit, is likely to vary widely across the state, as California climates range from cloudy temperate rainforest to sunny desert. Thus, to accurately estimate the impact of a large number of "cool roofs" in California it is necessary to collect and assimilate baseline data on incident radiation and current albedo of urban areas in the state.

**PREVIOUS WORK:** Investigators from Lawrence Berkeley National Laboratory, the National Center for Atmospheric Research, the Climate Institute, and the University of Almeria Spain have developed estimates of energy reduction (due to cooling load reduction) and general estimates of climate forcing benefits for indirect albedo associated with cool roofs and pavements, as well as shade trees. Lenton et al.[1] have provided pointed criticism of the general nature and methods of calculation for Akbari et al.[2] ARB-sponsored peer reviewers of Akbari et al. concluded that indirect albedo benefits of cool surfaces were real but suggested than California-specific data must be used to accurately and precisely estimate the state-wide climate forcing benefits for cool communities in California. Responding to this guidance and using the California Irrigation Management Information System (CIMIS) hourly broadband solar radiation data, ARB staff computed detailed, local (specific to CIMIS sites) fluxes of shortwave radiation for various areas of the state and then used these fluxes to estimate total cool roof indirect albedo climate forcing benefits for California.

**OBJECTIVE:** This project will collect and develop inputs of local urban core radiation and albedo necessary for improved estimates of the climate benefits of increasing urban albedo through the widespread application of "cool roofs". Additional funding would be needed to model the carbon dioxide ($CO_2$) equivalent total climate forcing benefits for cool roofs and pavements,

**DESCRIPTION:** Computing the benefit to climate of increasing urban albedo requires knowing the optical characteristics of old and new roofing materials, the applied roof area (horizontal surface "footprint"), and how much sunlight can be rejected back to space at the building site. This project will improve the model inputs for the first and last items. The current or baseline albedo of urban areas is typically treated in these types

of calculations as a single value, representative of global urban albedo. Actual urban albedo in California varies due to a number of factors such as roof color and amount of tree canopy. This proposal will use satellite albedo measurements available for seven major urban areas in California (Los Angeles, San Diego, San Jose, San Francisco, Fresno, Long Beach and Sacramento) and incorporate previous albedo approaches to create an albedo maps for California.

California's climate has a relatively large variation from cool, frequent overcast areas such as the north coast to hot and very sunny desert. To help manage irrigation resources, California maintains a broad network of 120 solar radiation measurement sites. However, none of the CIMIS sites are located in urban areas. Since it is not clear that CIMIS sites are representative of California's urban radiation flux this project will establish and monitor five solar radiation sites, three in major urban areas of diverse radiative strength and two co-located with existing CIMIS sites,

**BENEFITS:** The databases generated by this proposal will improve estimates of $CO_2$ equivalent climate forcing benefits of a program to increase urban albedo in California. If additional funding for the modeling effort were identified, the researchers developing the database in this project could interact and collaborate with the modelers, maximizing the utility of the database for radiative modeling. Improved confidence in the total benefits associated with "cool roofs" and, by analogy, "cool pavements", will allow regulators to properly include these benefits in efforts to mitigate the effects of climate change.

**COST:** $250,000

**REFERENCES:**


1. TM Lenton, ME Vaughn (2009). "The radiative forcing potential of different climate geoengineering options." *Atmos. Chem. Phys*., **9**, 5539–5561.
2. H Akbari, S Menon and A Rosenfeld (2009). "Global cooling: increasing world-wide urban albedos to offset $CO_2$" *Climatic Change*, **94**(3-4), 275-286, DOI: 10.1007/s10584-008-9515-9.

**TITLE: The role of land use planning in reducing residential energy consumption and greenhouse gas emissions**

**PROBLEM:** The vast majority of literature concerning the relationship between land use planning and greenhouse gas emissions has focused on the emissions from the transportation sector. This is understandable, since 55 percent of the emissions from the average California household stem from transportation.[1-3] However, researchers have largely ignored the relationship between land use planning and the next largest end-use sector—residences—which account for 37 percent of household emissions in California.[3, 4]

Roughly one-fifth of these emissions (or seven percent of the residential total) are due to heating and cooling, which are partly a function of house size and orientation, and therefore strongly tied to land use planning decisions. However, this share may increase substantially in the future as the state experiences rapid population growth in inland areas with hotter climates and greater temperature differentials. Many counties in San Joaquin valley are now growing at over twice the rate of relatively mild coastal metropolitan areas.[5] The California Department of Finance (2007) estimates that the state population will rise from roughly 37 million today to 60 million in 2050 – the very same period in which greenhouse gas emissions must be cut by 80 percent relative to 1990 levels. To accommodate this growth and still meet climate goals, the state must use every tool available to reduce emissions from all sources, including residential heating and cooling.

**PREVIOUS WORK:** The few academic studies that have examined residential energy use as a function of urban form[6-8] have concluded that residents living in high density urban centers emit 20 to 50 percent fewer greenhouse gases due to heating and electricity than residents of low density suburbs.[7,9] These studies have relied upon data sets created by national energy agencies, rather than more disaggregated state- or local-scale data that more accurately reflects local climatic conditions.

Portland Metro, the regional planning agency in the Portland, OR area, created a simple residential emissions spreadsheet modeling tool in 2007 that used more localized data. Portland General Electric (PGE) supplied Metro with data on average electricity consumption for households by occupancy and housing type. Using additional data compiled by the Northwest Power Coordinating Council (NWPCC), which collects sample usage data from Oregon, Washington, and Idaho, the relationship between energy consumption, square footage, number of occupants, and housing type could be modeled for differing socio-economic strata using ordinary least squares regression. The modeling tool has found, for example, that energy use and greenhouse gas emissions are roughly 30 to 50 percent lower per square foot in multi-family than in single-family housing, given roughly comparably residence size and socio-economic status.

**OBJECTIVE:** The objective of the project is to create a spreadsheet modeling tool that analyzes residential energy use within California climate zones as a function of land use planning factors.

**DISCUSSION:** The research would involve the following tasks:

1. Obtain disaggregate residential energy use data at an appropriate scale within selected California climate zones of interest.
2. Obtain relevant data on land use planning factors that may influence residential energy use, including housing type (e.g. single-family vs. multi-family), residence size, solar orientation, shading, and configuration of multi-family units; as well as other factors that contribute to household energy use, such as climate and number of occupants.
3. Conduct statistical analyses (likely using ordinary least squares regression) of the relationship between land use planning factors and residential energy use while controlling for other factors.
4. Create a spreadsheet modeling tool that estimates residential GHG emissions as a function of land use planning factors by climate zone. Depending upon the quality of energy use data available, this will likely involve applying regression coefficients to existing data for average consumption by occupancy and housing type to model energy use across relevant dependent variables.
5. Apply the statistical model to calculate average annual energy use and emissions estimates for selected housing types or other categories of consumers.

**BENEFITS:** These research results will support implementation of AB32 by allowing local governments to estimate the residential energy use and greenhouse gas emission implications of land use planning decisions about housing type, density, orientation and configuration. For example, these findings can directly support achievement of AB32's Green Building Strategy (strategy #13 in the Scoping Plan). They can also complement analogous information about the relationship of land use planning variables to vehicle miles traveled (VMT) and transportation energy consumption, the topic of an ARB-sponsored research project in 2009-2010. Together, these two spreadsheet models can inform a variety of local and regional planning processes, including general plans, building and zoning code updates, climate action plans, and long-term blueprint growth plans. They can also create an analytical framework for expanding SB 375 to apply to GHG emissions in sectors beyond transportation. In addition, these findings could also help establish clear thresholds of significance for climate change-related impacts under the California Environmental Quality Act for proposed new housing developments.

**COST:** $100,000

**REFERENCES:**


1. California Air Resources Board (CARB) (2008). Comparison of Greenhouse Gas Reductions for the United States and Canada under U.S. CAFE Standards and California Air Resources Board Greenhouse Gas Regulations. February 25th, 2008. California Department of Finance (2007). Population Projections by Race/Ethnicity for California and its Counties. July 2007. http://www.dof.ca.gov/research/demographic/reports/projections/p-1/ *Accessed December 4, 2009*.
2. Federal Highway Administration (FHWA) (2001). Do More Vehicles Make More Miles? A Snapshot Analysis of the National Household Travel Survey 2001. http://nhts.ornl.gov/2001/presentations/vehicleMiles/index.shtml *Accessed December 3, 2009*.
3. U.S. Environmental Protection Agency (U.S. EPA) (2009). Household Emissions Calculator. http://www.epa.gov/climate/climatechange/emissions/ind_calculator2.html. Accessed December 4th, 2009.

4. Energy Information Administration (EIA) (2005). 2005 Residential Energy Consumption Survey: Household Consumption and Expenditure Tables. Table US12. Total Consumption by Energy End Uses, 2005 - Quadrillion British Thermal Units (BTU)
5. Senate Bill 375 Regional Targets Advisory Committee (RTAC) (2009). MPO Scenario Data Spreadsheet. http://www.arb.ca.gov/cc/sb375/rtac/meetings/081809/scenariodatasheet2.xls *Accessed October 5, 2009*.
6. Ewing, Reid, and Fang Rong (2008). The Impact of U.S. Urban Form on Residential Energy Use. *Housing Policy Debate* 19(1): 1-30.
7. Norman, Jonathan, Heather L. MacLean, and Christopher A. Kennedy (2006). Comparing High and Low Residential Density: Life-Cycle Analysis of Residential Energy Use and Greenhouse Gas Emissions.
8. VandeWeghe, Jared R., and Christopher Kennedy (2007). A Spatial Analysis of Greenhouse Gas Emissions in the Toronto Census Metropolitan Area. *Journal of Industrial Ecology* 11(2), 133-144.
9. Ewing, Reid, Keith Bartholomew, Steve Winkelman, Jerry Walters, and Don Chen (2008). *Growing Cooler: The Evidence on Urban Development and Climate Change*. Washington, DC: Urban Land Institute, 2008.

**TITLE: Development and evaluation of energy-efficient approaches to keeping building occupants cool using room air motion**

**PROBLEM:** Moving air cools the human body. In warm conditions, it can provide the same comfort as compression-based air conditioning, but at lower energy cost. Fans of very low wattage (as low as 3W for a personal fan) can produce 1 m/s (2 mph) near the occupant, offsetting 3K (6ºF) of air temperature. The savings in HVAC energy is substantial (over 30% of cooling HVAC energy in mechanically conditioned buildings),[1] and greater if the fans enable the building to be successfully conditioned by natural ventilation or evaporative cooling systems, instead of chillers. In the past, air movement technology has been impeded by contrary standards, and there has been little innovation in the industry. The products on the market are mostly a limited set of generic ceiling, desk, and stand fans.

The challenge is to implement air movement in ways that are highly energy efficient, comfortable, and acceptable to occupants, as well as visually attractive to building management and designers. A few prototype systems meeting these criteria have been quantified in recent tests. Prototypes included fan and nozzle configurations that could be attached to office furniture, partitions, and ceilings. They were silent and could be reliably controlled with occupancy sensors. The opportunities for design improvements and new products are great. However, architects, interior designers, and manufacturers lack evidence that realistic configurations of fans can provide a high-quality comfort environment at low energy cost. This evidence is needed to encourage such a major change in indoor environmental control.

**PREVIOUS WORK:** In the past, ASHRAE Standard 55 restricted the use of air movement by treating it as draft. This has now been changed following Center for the Built Environment (CBE) findings that large majorities of office occupants prefer increased air movement.[2,3] The standard now contains robust provisions for using air movement cooling in warm environments.[4]

CBE has a history of studying air movement for comfort in both laboratory and field studies. Early laboratory studies showed that comfort can be well-maintained by air movement in high ambient temperatures as high as 82ºF and 86ºF.[5,6] Recent laboratory studies show that a 3W personally ventilated fan can make people comfortable at high ambient temperatures.[7] These studies also showed that air movement significantly improved people's perceived air quality, possibly by disrupting the body's thermal plume in which pollution is carried to the breathing zone. Field studies have shown personally controlled air movement systems to be highly popular in offices.[8] Currently CBE is designing several prototypes of low wattage personal fans/nozzles standing alone or combining with furniture (about 3W, with occupancy sensors) and will install approximately 200 of them in two to three naturally ventilated buildings (funding has been approved from CEC/PIER).

**OBJECTIVE:** Promote the use of fan-powered air movement to reduce compressor-based cooling in office buildings through the following steps:

- Test combinations of nozzles and propeller fans mounted on or in office furniture, partitions, and ceiling panels. Collaborate with CBE industry partners to integrate

fans in their products: e.g., Armstrong for acoustic ceilings, Haworth and Steelcase for office furniture and partitions.
- Characterize the physiological cooling effect for these combinations using the CBE thermal manikin. Quantify how much the ambient indoor temperature range can be expanded.
- Test human subjects to quantify their comfort and satisfaction under long-term and short-term transient exposures. Characterize their use of personal environmental controls.
- Prepare a report for designers, owners, and manufacturers of interiors and furniture systems.

**DISCUSSION:**
Primary tasks include:
- Install ceiling and personal fans in four configurations (integration of ceiling fans/nozzle jets with suspended ceilings, personal fans with partitions and furniture, ceiling fan and personal fan alone or combinations of both). Investigators will set up one workstation in the chamber. One ceiling fan and one personal fan will be tested in each test configuration, but the types of fans will be changed in successive tests. Investigators will choose and test fans with low wattage inputs. Some of the ceiling fans and personal fans will be unique designs or modifications of existing fans.
- Measure the velocity profiles of various configurations, and heat loss from a 16-body segmented thermal manikin.
- Conduct human subject test in the CBE environmental chamber to determine the effect of air movement on human thermal comfort from different types of fans and modes of installation; optimize the configurations of the fan types, speed, installations. Thirty human subjects will each participate in all four test configurations. Transient effects on comfort will be examined between the different test configurations.

In all, the total number of human subjects tests will be 120 (4 configurations x 30 subjects/configuration).

**BENEFITS:** This study will directly support designs of naturally ventilated buildings. The use of well-designed fans makes naturally ventilated building designs more feasible for the times when wind is weak. They also extend the outdoor temperature range within which less powerful evaporative or ground-source cooling sources may be used. Fans also strengthen the effectiveness of other energy-efficient measures which may be inherently slow-acting or unpredictable, such as radiant ceilings/floors.

Room fans have advantages in both new and retrofit designs since they do not involve other HVAC systems, can be easily turned on and off (as with occupancy sensors or wireless controls), and they can provide instantaneous comfort. Well-integrated fan systems are both cost effective and energy effective.

There may be health benefits as well. Several large field studies surveying people in office buildings have found that sick building syndrome is significantly less in the NV buildings than in the HVAC buildings.[9,10]

**CO-FUNDING:** This project will be coupled with two CEC/PIER projects: in "Advanced Integrated Systems Tools Development and Performance Testing," investigators are designing and manufacturing several low-wattage prototype fan units for use in office workstations and furniture ($190,000), and improving EnergyPlus to better predict energy use by integrated fan systems. In the "Natural Ventilation for Energy Savings in California Commercial Buildings," investigators will monitor occupants' use of these fans and their satisfaction with them over a year in an office building ($180,000).

**COST:** $150,000

**REFERENCES:**


1. Hoyt, T., H.L. Kwang, H. Zhang, E. Arens, T. Webster (2009). "Energy Savings from Extended Air Temperature Setpoints and Reductions in Room Air Mixing," *International conference on Environmental Ergonomics,* Boston, August 2-7.
2. Hoyt, T., H. Zhang, E. Arens (2009). "Draft or Breeze? Preferences for Air Movement in Office Buildings and Schools from the ASHRAE Database, *Healthy Buildings,* Syracuse NY, Sept 13-17.
3. Zhang, H., E. Arens, S. Abbaszadeh Fard, C. Huizenga, G. Paliaga, G.Brager, L. Zagreus (2007). "Air Movement Preferences Observed in Office Buildings," *International Journal of Biometeorology*, 51: 349-360.
4. Arens, E., S. Turner, H. Zhang, G. Paliaga (2009). "A Standard for Elevated Air Speed in Neutral and Warm Environments," *ASHRAE Journal*, May 51 (25), 8-18.
5. Fountain, M., E. Arens, R. de Dear, F. Bauman, K. Miura (1994). Locally Controlled Air Movement Preferred in Warm Isothermal Environments, *ASHRAE Transactions,* 100 (Part 2): 937 – 952
6. Arens, E., T. Xu, K. Miura, H. Zhang, M. Fountain, F. Bauman (1998). "A Study of Occupant Cooling by Personally Controlled Air Movement," *Building and Environment,* 27: 45 – 59.
7. Zhang, H., E. Arens, D. Kim, E. Buchberger, F. Bauman, and C. Huizenga (2010). "Comfort, Perceived Air Quality, and Work Performance in a Low- Power Task-Ambient Conditioning System," *Building and Environment* 45(1), 29-39.
8. Bauman, Fred, Carter, T., & Baughman, A. (1998). Field Study of the Impact of a Desktop Task/Ambient Conditioning System in Office Buildings. *ASHRAE Transactions,* 104, part 1, 19pp.
9. Fisk W.J., M.J. Mende11, J.M. Daisey, D. Faulkner, A.T. Hodgson, M. Nematollahi and J.M. Macher (1993). "Phase 1 of the California Healthy Building Study: A Summary," *Indoor Air*, 3, 246-254.
10. Zweers, T., L. Preller, B. Brunekreef, J.S.M. Boleij (1992). "Health and Indoor Climate Complaints of 7043 office Workers in 61 Buildings in the Netherlands," *Indoor Air*, 2, 127-136.

**TITLE: Using feedback from commercial buildings to support energy-conserving behavior at work and at home**

**PROBLEM:** In 2006, California's residential buildings produced 34MMT of greenhouse gases (GHGs), while commercial buildings produced 14 MMT of GHGs.[1] Many efforts advance technological solutions for this problem. Yet, few people purchase such technologies for their homes; and interest in buying such technologies remains low. People are, however, generally interested in learning about their energy use.[2] This suggests that GHG reductions from residential sources may be achieved through social and behavioral approaches. Uptake of energy-conserving technologies is better among commercial buildings; however, occupant impacts often increase energy use far above expected levels.[3] For example, when occupants view building technologies as inconvenient, they may disable them.[4-6] Thus, occupant behavior is an important part of energy use and GHG reductions in the commercial realm as well. This research will look at a single method to reduce both residential and commercial GHG emissions.

**PREVIOUS WORK:** Recent articles have touted the energy savings offered by building feedback systems.[7-9] What is missing is a discussion of the population using these devices. Opt-in techniques generally attract homeowners that are already interested in resource-efficiency, those who have already taken steps to reduce their carbon footprint.[10] Comments from the CBE survey database suggest that a similar dichotomy of users exists in the commercial realm.[11] There is much research about the technological requirements of creating feedback outlets for occupants, and some discussion of potential energy use reductions among the motivated. Little work has focused on these systems' abilities to change motivations and behavior for the unmotivated. CBE has developed and widely used a survey designed to gauge opinions about buildings, their energy efficiency and their environmental conditions. This tool can be used in conjunction with CBE's newly developed building feedback systems to investigate the issue.

**OBJECTIVE:** The project has three objectives. It will identify the kinds of energy conservation-related information most likely to influence different segments of the workforce. It will quantify the degree to which this information affects energy-conserving beliefs and behaviors at work and at home. It will also quantify the GHG reduction potential associated with the stated behaviors.

**DISCUSSION:** At the conclusion of a CBE-funded pilot test described in the co-funding section, CBE will identify up to three buildings for installations.[2] One site will receive an information-only feedback system mirroring the industry standard. This will serve as the control case. The other sites will receive CBE's enhanced feedback systems. Occupants at each site will interact with the systems for six months. Occupants will be surveyed at the beginning and end of the implementation using largely identical questionnaires. In addition to demographic and psychographic batteries, they will be asked about their energy-related beliefs and actions at work and home. The survey will not gather any identifying information. After gathering the data, CBE will compare

[2] Several industry partners and research affiliates have expressed interest.

occupants' energy-conserving beliefs and actions before and after interacting with the feedback system as well as across demographic and psychographic groups. Differences between occupants that interacted with the standard and enhanced systems will also be analyzed. The reported behaviors will then be translated into energy and GHG reductions.

**BENEFITS:** This work will create a useful tool that the building industry may use for actual energy reductions, and thus GHG reductions. The results may also encourage more building owners to include such systems and policymakers to develop incentives for their inclusion in more buildings. The project will also be one of very few to report on potential to motivate the large portion of the population that has yet to take action to reduce GHG emissions through decreased energy use.

**CO-FUNDING:** CBE's industry partners provide ongoing support for the building occupant survey tools and have co-funded-- with the California Energy Commission PIER Program-- a research project to develop and test new types of building feedback for occupants. Funding from California ARB will support the next phase of this work: integration of the survey and feedback tools, and the installation of the systems into three buildings.

**COST:** $185,000

**REFERENCES:**


1. California Air Resources Board (2010). California Greenhouse Gas Emissions Inventory. Sacramento. http://www.arb.ca.gov/cc/inventory/inventory.htm.
2. Mintel Reports (2009). "Smart House - US - April 2009," *Mintel Reports*. http://academic.mintel.com/sinatra/oxygen_academic/my_reports/display/id=418746&anchor=atom/display/id=455713?select_section=455714
3. Masoso, O. T. , and L. J. Grobler (2010). "The dark side of occupants' behavior on building energy." Energy and Buildings. 42.2: 173-177.
4. Embrechts, Rob, and Chris Van Bellegem (1974)."Increased energy savings by individual light control." In *Proceedings of Right Light 4*. Volume 1.
5. Vaidya, P., T. McDougall, D. Eijadi, J. Douglas, and J. Steinbock (2004). "What's Wrong with Daylighting. Where it Goes Wrong and How Users Respond to Failure," pp. 7.342-7.357, 2004 ACEEE Summer Study on Energy Efficiency in Buildings. Washington, D.C.: American Council for an Energy Efficient Economy.
6. Vaidya, P, T. McDougall, J. Steinbeck, J. Douglas, and D. Eijadi (2005). "Making Daylighting Work: Learning from Failures to Improve the Design and Implementation Process," pp. 563-570, 2005 ECEEE Summer Study on Energy Efficiency. Stockholm: European Council for an Energy Efficient Economy.
7. Mountain, Dean (2006). Impact of Real-Time Feedback on Residential Electricity Consumption: The Hydro One Pilot. Hamilton, Ontario: McMaster Institute for Energy Studies.
8. Darby, Sarah (2006). The Effectiveness Of Feedback On Energy Consumption: A Review For The DEFRA Of The Literature On Metering, Billing And Direct Displays. Oxford: Environmental Change Institute.
9. Parker, Danny, David Hoak, and Jamie Cummings (2008). "Evaluating Energy Use Feedback Devices." *Home Energy*. June/July.
10. Moezzi, Mithra (2008). "2007-2008 SMUD PowerChoice Time of Use Program: DRRC Research Projectq." Proceedings of California Energy Commission Load Management Standards Efficiency Committee: Customer Education and Need Workshop. Sacramento.
11. Moezzi, Mithra, and John Goins (2010). "Using Text Analysis to Listen to Building Users." Proceedings of Adapting to Change: New Thinking on Comfort. Fergus Nicol: Windsor, UK.

**TITLE: Reducing energy use through optimized communication of real-time residential energy usage information**

**PROBLEM:** California must reduce GHG emissions by 30 percent over the next decade to meet goals set by AB32. In the realm of electricity, recent focus has emphasized increasing the share of renewable power sources on the grid, with less attention given to demand management. Recent studies estimate that behavioral changes can reduce residential energy consumption by between 22 and 30 percent over the next 5 to 8 years[1,2] To foster reduced residential energy consumption, high-resolution energy metering and electrical sub-meterings with dashboard displays are being rolled out across California. One of the potential benefits of these displays is that consumers can receive more information (feedback) about their electricity usage. This increased level of feedback is intended to empower consumers to make better decisions and cut back on their electricity usage. But given the high costs of action, and the low marginal costs of electricity, will consumers actually behave in this manner? Surprisingly little work has been done on the subject, with most previous studies involving small samples of homes and yielding mixed results. Indeed, some studies suggest that more information can lead to an increase in electricity usage.[3] Motivating energy-conserving behavioral change through provision of information requires a clear understanding of how target audiences respond to various styles and content of communication.

**PREVIOUS WORK:** In a survey of previous studies, covering a multitude of feedback mechanisms, Fischer (2008) reports that feedback results in a reduction of electricity usage of between 1.1 and 20 percent.[4] The majority of these studies surveyed took place in Europe, with only 3 out of 26 taking place in the United States. Many U.S. colleges have experimented with feedback mechanisms following a successful study at Oberlin College, where a mixture of dormitory-level feedback and competition between the dormitories reduced electricity usage by 32 percent over a two-week period.[5] OPower offers consumers feedback on neighborhood-level norms for electricity usage and find that electricity usage is reduced by an average of 2.5 percent. There is, however, significant heterogeneity in this result, with some users increasing their electricity usage. A formal evaluation is forthcoming. In California, a number of utilities are currently installing Smart Grid systems with possible real time consumer feedback. It remains to be determined how this information will be presented and how its effects will be evaluated.

**OBJECTIVE:** The goal of this project is to determine how to best present electricity usage information to heterogeneous electricity consumers so as to induce conservation. To this end, investigators will test and evaluate a number of non-pecuniary interventions based on increased feedback (information) to customers. Private information is information about an individual's usage that is available strictly to the individual. Public information is usage information that is available in the public realm, either at the aggregate or individual level. Varying the quantity and type of public and private information available will help investigators clarify the linkages between personal responsibility, social norms and social pressure/status effects. Investigators will also probe how the connection between new information and existing preconceptions about electricity usage leads to behavior change.

**DISCUSSION:** Residents of college dormitories face no marginal cost for electricity consumption. As a result, they have no financial incentive to curtail their usage. This makes them a convenient study group for pure information effects.

Investigators have developed the technology to wirelessly monitor plug load, lighting and HVAC usage within a room and have the funding to conduct a pilot study at UCLA. Investigators are currently in the process of installing electricity monitors in 90 dorm rooms. These monitors will give real-time room level feedback on electricity usage. The goal of this pilot is to determine if an incentive structure based on personal responsibility (through providing real-time, room-level energy consumption information) and social pressure (by sharing energy consumption information within the residence hall community) effectively encourages energy conservation.

The proposed effort will expand upon this ongoing pilot project to enable a larger number of treatments as well as include users with apartment-style living arrangements. Several private information treatments will be devised, in which investigators will vary the type of information that is available and evaluate how different consumers respond to this information. Private information can vary according to the units presented ($CO_2$, kWh, ecological effects, etc.), the time period presented (real time usage, daily usage), the method of aggregation (deviations from the user's norm, deviations from the group norm), and the mode of presentation (chart, display dial, animated picture, etc.). Several public treatments are also proposed, in which investigators will vary what other people know about the user (full disclosure of all usage, voluntary disclosure of top energy savers, involuntary disclosure of energy "hogs"), as well as what the user knows about others (average usage, usage of neighbors most similar, average improvements of other users, etc.). The study will expand from 80 rooms in the pilot to an entire residence hall (300 rooms) and to 200 graduate student family apartments.

**BENEFITS:** A large number of utilities are rolling out Smart Meters that have the capabilities for real-time feedback to consumers. However, there is a lack of research regarding how information can be used as to promote residential electricity conservation. Better knowledge on how consumers respond to this information and how to best share this information with consumers will serve to reduce aggregate electricity demand and help California meet its obligations under AB32. Lessons learned can also be applied to universities across California to reduce the State's electric bill.

**CO-FUNDING:** Investigators have received $15,000 from UC Centre for Energy and Environmental Economics (UCEEE), and $42,000 from The Green Initiative Fund at UCLA for a pilot study.

**COST:** $330,000 (Based on 10% overhead. Original request figured 54% UCLA overhead for total requested $461,722.)

**REFERENCES:**


1. Laitner J., Ehrhardt-Martinez, K. & Vanessa McKinney (2009). "Examining the Scale of the Energy Efficiency Continuum", in Proceedings of 2009 ECEEE Summer Study. La Colle Sur Loup, Cote d'Azur, France
2. Gardner, G. and P. Stern (2008). "The Short List: The Most Effective Actions U.S. Households can take to Curb Climate Change." *Environment* 50(5), 12-24.

3. Brandon, G., & Lewis, A. (1999). “Reducing household energy consumption: a qualitative and quantitative field study.” *Journal of Environmental Psychology,* 19, 75–85.
4 Fischer, Corinna (2008). “Feedback on household electricity consumption: A tool for saving energy?” *Energy Efficiency*, 1:79–104.
5. Petersen, J., Shunturov, V., Janda, K., Platt, G. & K. Weinberger (2007). “Dormitory residents reduce electricity consumption when exposed to real-time visual feedback and incentives.” *International Journal of Sustainability in Higher Education,* v.8(1), pp.16-33

**TITLE: Monitoring and evaluating strategies for changing behavior using the CoolCalifornia.org resource developed by ARB**

**PROBLEM:** Evidence from social psychology indicates that improved access to information does not suffice to motivate individuals and communities to take action, even when action is rational and/or in the audience's best interests. In addition to information, individuals' values, habits, abilities, worldviews, and social and economic constraints are among the factors influence behavior. Social psychologists contend that it is critical to tailor information-based messages to different audiences and to leverage social motivations for behavior change. For example, encouraging individuals to make public commitments, fostering group identification, and developing competitions have all been demonstrated as effective strategies to foster behavior change. As articulated in the Scoping Plan, voluntary emissions reductions will play a critical role in meeting California's climate change goals. Hence, understanding how to motivate voluntary emissions reductions is a crucial part of the State's climate change strategy.

**PREVIOUS WORK:** In November 2008, ARB partnered with UC Berkeley (UCB) to develop interactive, advanced California-specific consumption-based carbon footprint calculators for households and small businesses. The intention of developing calculators is to support voluntary emissions reductions. The first phase of the project has produced sophisticated calculators that incorporate advanced life cycle assessment, carbon footprint benchmarking, financial and greenhouse gas scenario building, GIS-based carbon footprint maps, and online community social networking.

Starting in early 2010, versions of the CoolCalifornia Calculator and the full CoolClimate Calculator are being extended to communities and organizations throughout California and the nation. Each community will use the calculator in a somewhat different way. For example, volunteers in Monterey and Santa Cruz counties will go to hundreds of households door-to-door, initially targeting low income communities; Davis is already bringing hundreds of households together physically and online to tack progress toward commitments using the calculator; Berkeley is conducting dozens of workshops and training trainers to conduct programs in schools; and each of these communities is interested in engaging in competitions both within and between communities. Other organizations will model similar initiatives on the success of these pilots.

**OBJECTIVE:** This investigation will provide the state with empirical evidence from a California-based study to help illuminate barriers to adopting climate-friendly behaviors. Specifically, this work will 1) assess total greenhouse gas emissions reduced via a variety of projects involving CoolCalifornia and CoolClimate resources, 2) illuminate how new information tools can be most effectively used by the State to encourage more sustainable behavior, and 3) compare the behavioral changes induced by different community-based greenhouse gas reduction programs in California.

**DISCUSSION:** Ongoing, voluntary community initiatives that incorporate CoolCalifornia resources into efforts to reduce GHG emissions provide excellent opportunities to test the effectiveness of different messaging strategies, community participation models,

and social marketing techniques and theories to demographically and geographically distinct audiences.

In addition to assessing ongoing initiatives involving CoolCalifornia, the investigator will conduct a randomized controlled study to monitor and evaluate the effectiveness of different program models using the CoolCalifornia calculator and to test social marketing and social networking strategies that build on behavioral psychology theory. Participating households will be asked to make pledges for GHG emissions-reducing actions. Households will be contacted several times over the study period allowing us to track compliance with pledge commitments under different program models. Investigators will track users' carbon footprints, commitments, pledges and profile information, including location and demographic variables. Quantitative analysis of household data will be complemented by interviews to discern what features of the programs were (or were not) meaningful, motivational, and effective to the participants.

Additionally, staff is in discussion internally and with UCB researchers to identify a simple pilot strategy that households can adopt to reduce emissions, and to design a voluntary intervention effort for testing and evaluation. The objective of this effort is to craft low-cost interventions that are replicable across the State. Appropriate pilot strategies will be low-cost, based on readily adoptable behavioral change, and build on tools developed by the State.

**BENEFITS:** This investigation will add significantly to the State's understanding of how to effectively motivate voluntary GHG emissions reductions and energy conservation by providing empirical evidence from a California-based study. The results will be directly relevant to ARB, as the initiatives to be tested involve a resource developed by ARB in collaboration with UCB for promotion of voluntary emissions reductions by households and small businesses in California.

**CO-FUNDING:** The calculator has already has hundreds of thousands of users. By working with programs in different communities that are actively engaged with households we will be able to provide monitoring of data collection and verification of results. Several communities are already enthusiastic about participating in such a study and will supply staffing and trained volunteers to conduct much of the data collection.

**COST:** $300,000

## APPENDIX D: Concepts Recommended for Technology Research and Development

### Table of Contents

**TITLE: Zero on-site pollution for portable power applications including generators and lawnmowers**

**PROBLEM:** Over 5.85 Million lawnmowers were purchased in 2004 and only 13% of the purchased mowers were electric. The vast majority of heavy users such as professional landscapers only use combustion based lawnmowers. Lawnmowers continue to be a significant pollution source. It has been estimated that 15% of GHG emissions come from small spark ignition engines and 5% from lawnmowers alone. While improvements in small combustion engine technology are occurring, engines continue to be a major source of pollution especially when considering the relatively small amount of energy consumption. Electric lawnmowers are effective for some homeowners but even the most advanced battery technology is not capable of providing a reasonable solution for professional landscape crews and the bulk of small combustion engine users.

Hydrogen fuel cells can run at very high efficiencies with near zero on-site pollution. However, hydrogen production, storage, and distribution issues continue to encompass the most significant set of challenges impacting practical fuel cell commercialization. Small combustion engines are a strong contender for early fuel cell adoption as they are highly polluting, have poor energy efficiency, and may potentially be serviced with existing distribution channels. A hydrogen storage solution is required with low cost, low operating pressure, easy-to-use operation, and has high energy/power density.

**PREVIOUS WORK:** SiGNa Chemistry is based on the company's core technology for transforming reactive alkali metals and their derivatives into safe, free-flowing powders. Sodium silicide, NaSi, produces up to 10 wt.% hydrogen just from the reaction with water. The production of hydrogen can be controlled by the rate of water addition. Hydrogen can be generated on demand for portable applications such as: personal mobility, backup power, emergency power, and small combustion engines. The reaction by-product is a common industrial chemical, $Na_2Si_2O_5$, which is benign creating no risk to the environment and has an array of industrial uses. The chemical reaction is as follows:

$2NaSi(s) + 5H_2O(\ell)\ 5H\Diamond_2(g) + Na_2Si_2O_5(aq)$

The net result is a lightweight, packaged fuel which generates hydrogen at a nominal pressure of 15 psi. With packaging, the fuel energy density is approximately 1400 W-Hr/kg. For comparison, high-performance / high-power batteries store energy at below 60 W-Hr/kg. This translates to a 20X decrease in weight as compared to batteries which makes sodium silicide a strong contender for a range of portable power applications like lawnmowers. SiGNa has demonstrated the technology on electric bicycles and small generators capable of 300 Watts of continuous power. Initial research indicates lawnmowers require an average power of 750 to 1500 Watts. The NaSi reaction is readily capable of generating the higher required flow rates. However, an improved cooling system and a scaled-up water feed system is required. SiGNa has separate activities in place to ramp up manufacturing of the raw materials themselves.

**OBJECTIVE:** The proposed research will result in the demonstration of a sodium silicide fueled lawnmower. The developed system will look and feel like a professional product. The demonstrated designs will be suitable to serve as the template for production ramp. A significant technical focus will include the reaction control, thermal management, and fuel cell systems integration. The specific objectives are as follows:

1. Demonstrate the reaction control system to support a nominal ~1 kW fuel cell output
2. Demonstrate the thermal management system with safe-to-touch swappable cartridges
3. Demonstrate a fuel cell powered lawnmower fueled by sodium silicide

**DISCUSSION:** The Work Plan for the proposed work is summarized by the following:

**Task 1.0 Hydrogen Fuel Cell System Requirements Development.**
The hydrogen fuel cell system requirements will be developed for an early market application with high volume potential: lawnmowers. Using available operational data, specific requirements for a fuel cell system for areas including: duty cycle, peak power modes (thick grass patch), or transient conditions (motor start-up).

**Task 2.0 Development of Reaction Control Mechanisms**
SiGNa will scale-up its reaction control mechanism from the currently capable 300 W system to approximately 1 kW. A small water pump is used to inject a water mist into a reactor bed. The scale-up will include design, assembly, and testing of all management and other reaction control features. A similar design will be employed as compared to what has been previously demonstrated, but different pumps and misting networks are required.

**Task 3.0 Development of Thermal Control Sub-System**
To date, SiGNa has focused on simple air cooled systems. SiGNa will develop a liquid cooled heat exchanger system suitable for small portable devices to control the reaction as well as provide surfaces that may be readily touched by the user when swapping cartridges.

**Task 4.0 Development and Integration of Fuel Cell Powered Lawnmower**
SiGNa will procure an electric lawnmower and fuel cell system from known partners. SiGNa will perform the final end system design and integration. This program will also include the final assembly, testing, and demonstration of the NaSi Lawnmower.

**Task 5.0 Program Management.**
Reporting and program management functions.

**BENEFITS:** The developed technology will foster an entire new industry of clean portable energy systems. In addition to immediate reductions in small combustion engine pollutants, this program will be supported by multiple known individuals and companies in California including machining in Placerville and Sacramento, injection molding in Vacaville, and system assembly in the San Francisco Bay Area. These partners have significant technical expertise and available capacity to support the

program and more importantly to grow into a viable portable power industry. SiGNa's sodium silicide enables energy systems that are based on US produced raw materials and will provide substantial value to both military and consumer applications. One of the primary material components, sodium, is produced in New York based on energy from Niagara Falls. However, all of the system design, integration, and assembly work is conducted in California. This industry can readily generate 1000's of California jobs when fully commercialized.

**CO-FUNDING:**
*The development budget is $470,000*. 20% cost share is proposed. $376,000: Air Resources Board, $94,000: SiGNa Chemistry.

*Federal Funding Received*: In 2008-2009, SiGNa received $1,476,000 from the Department of Energy for material production and reaction mechanism development. An additional $951,500 is currently under contract for 2010.

*Private Funding*: SiGNa has contributed approximately $4M in private funding to date.

*Potential Funding*: SiGNa has requested additional development funds for supportive projects both through appropriations and the SBIR process.

**COST:** $376,000

**REFERENCES:**

1. EPA site: http://www.epa.gov/glnpo/greenacres/nativeplants/factsht.hmtl, accessed November 2008
2. J. Dye, et. al, "Alkali Metals Plus Silica Gel: Powerful Reducing Agents and Convenient Hydrogen Sources," JACS Communications, June 14, 2005
3. M. Shatnawi, et. al, "Structures of Alkali Metals in Silica Gel Nanopores: New Materials for Chemical Reductions and Hydrogen Production," JACS Artichels, January 17, 2007
4. A. Wallace and S. Shah, "Advances in Chemical Hydride Based PEM Fuel Cells for Portable Power Applications," 2007 Joint Service Power Expo: *"Power & Energy Independence for Warfighters"*, San Diego, CA, April 24-26, 2007
5. A. Wallace and M. Lefenfeld, "NaSi and NaSG Powder for Hydrogen Fuel Cells", DOE Annual Merit Review, May 2009
6. A. Wallace, et. al, "Challenges and Opportunities in Deploying Commercial Fuel Cell Systems," Small Fuel Cells for Portable Applications, 8th Edition, 2006

**TITLE: An improved particle concentrator for inhalation studies**

**PROBLEM:** Numerous epidemiological studies associate particle concentration exceedances with a range of pulmonary, cardiovascular and systemic health effects, yet toxicological support for these finds are elusive. One common technique is exposing laboratory animals to concentrated ambient particles to elicit health effects. There are two commonly available concentrators, developed by investigators at Harvard and the University of Southern California (USC), both with their strengths and weaknesses. In a previous CARB contract, we investigated some possible artifacts with USC concentrated (called VACES) both in terms of chemical composition of the gas phase and reliability of the particle phase. In a small follow-on subcontract, we improved VACES in a number of ways outlined in our final report to CARB but still the concentrating ability is insufficiently steady with time and overly dependent on ambient temperature, RH and particle concentration. Aerosol Dynamics has invented a water-based CPC (WCPC) that grows particles reliably over a wide temperature and RH range and a focusing virtual impactor that lowers the cutpoint substantially. Recently they applied the WCPC principle to the design of a 100 L/min system for particle collection. We propose to translate these Aerosol Dynamics innovations to a more efficient particle concentrator and test the resulting concentrator on a wide range of ambient conditions.

**PREVIOUS WORK:** UC Davis (UCD) investigators have tested VACES for both chemical and physical artifacts, reported on these in our final report to CARB and in a manuscript that is nearly accepted for publication. UCD has also made significant improvements to VACES, also discussed in our final report, that also outlines a number of ways in which the improved VACES can be further improved, especially for long-term operation and stability. Aerosol Dynamics invented the water-based CPC (WCPC) that is now built and marketed by TSI. The WCPC does many of the same tasks as the VACES in that it grows particles by condensation of water, but at much lower flow rates than the VACES. In addition, Aerosol Dynamics has recently invented a focusing virtual impactor with low cut point that also has low flow rate but that when scaled to VACES flow rates can help its performance during high particle loadings.

**OBJECTIVE:** The objective of this proposal is to establish a joint research program between Dr. Wexler's group at UCD and Dr. Hering's group at Aerosol Dynamics (AD) bringing the features developed by both groups together to develop a version of VACES that, in terms of its concentration factor, is nearly insensitive to ambient conditions and can operate for long periods of time with minimal or no attendance.

**DISCUSSION:** We will develop 100 LPM modules that concentrate by a factor of 20 with little or no maintenance over a 6 hour exposure period. The modules may be ganged together to build concentrators of arbitrary capacity to meet the needs of field toxicology studies. The WCPC must be laminar to operate properly, which imposes a range of constraints at the 100 LPM design goal, whereas the VACES developed by USC and the current version of iVACES developed at UCD are turbulent. To improve its long-term operation and stability, UCD has developed a Hybrid iVACES that cools both before and after the warming/humidifying stage. The first cooling stage narrows the range of ambient conditions that the warming section has to deal with thereby making

the iVACES less sensitive to ambient conditions. All designs will employ the iVACES Nafion dryer eliminating maintenance problems and returning the particles to near ambient temperature and RH.

The current VACES and iVACES are not able to effectively concentrate high ambient particle concentrations due to a lack of available water content. Aerosol Dynamics has developed a virtual impactor with a smaller cut point than used currently, which will enable operation at ambient concentrations more common in plumes.

AD Tasks

1. Scale up the WCPC and recently-developed focusing virtual impactor to 100 LPM flow rates
2. Deliver the devices to UC Davis for testing
3. Iterate the designs based on tests by UC Davis

UCD Tasks

1. Test the hybrid iVACES with current and focusing virtual impactors at high particle concentration
2. Test the scaled up WCPC with both impactors at normal and high particle concentrations
3. Test the most promising configurations in multiple seasons for 6-hour runs to explore sensitivity to ambient conditions and its durability/reliability
4. Iterate designs in response to these tests

**BENEIFITS:** California violates the state and national ambient air quality standards for particulate matter in multiple air sheds, resulting in illness and death for large numbers of Californians. One well-accepted way to help establish safe PM levels and understand the relative toxicity of various sources of PM is to perform concentrated ambient particle toxicity studies. Yet the concentrators are difficult to operate reliably which introduces artifacts into these studies. The current project will develop a much more reliable and stable particle concentrator that will enable improved particle toxicity studies in the future.

**COST:** $150,000