Chapter 6: Conclusions and Recommendations

The RESAVE program has been very successful from an RD&D perspective. This can be judged by the three dozen technical products listed in this report. This number far exceeds the number that could be generated by the RESAVE resources alone and was accomplished by leveraging RESAVE resources with industry and federal programs as described above.

The list of technical products RESAVE can take credit for is not complete, because at the time that this report is being written, continuing work (supported by cost-share partners) will result in additional technical products. To see the most recent set of technical results, please consult the RESAVE website, at http://resave.lbl.gov.

6.1 Key Findings

Each section and each technical product discusses specific research findings. Below are some key findings.

6.1.1 Industrial Cooperation

A key enabling (rather than technical) finding is that partnering with industry has led to a more rapid development and adoption of technology and related R&D than would have been accomplished without such collaborations. Working with Panasonic, for example, has led to more rapid update of RESAVE products in the market, and well as more rapid advancement of ASHRAE Standard 62.2. Working with DuPont has led to improved air leakage standards and clarified the value of air-tightness.

6.1.2 Air Leakage

6.1.2.1 Residential Diagnostics Database

Analysis of the data for both the United States as a whole and for California allows us to determine tendencies and correlations of the air-tightness of building envelopes with building properties. These findings are needed to estimate energy demand associated with heating and cooling, and also the potential energy savings from air-tightening. Some important findings are summarized below:

- Homes that were built (or retrofitted) to be energy efficient (in some sense) are generally 30 percent tighter than conventional homes.
- Low-income homes, (such as those that qualify for the Weatherization Assistance Program (WAP), are generally 50 percent leakier than conventional housing.
- A typical air-tightening retrofit reduces leakage by 20 percent for conventional housing and 30 percent for low-income housing.
- Coastal homes (e.g., California climate zone 2) are leakier than most homes, correcting for all other factors. Houses in California climate zones 13 and 14 are over 20 percent tighter than coastal homes.

- Houses built over the past five years (since 2008) are over 20 percent tighter than those built a decade earlier.

6.1.2.2 Multizone Leakage

Simulation and field analysis of multizone, blower-door base, air-leakage techniques have enabled us to identify different methods for measuring residential leakage, both to the outside and to adjacent spaces. The methods considered are applicable to both multifamily homes and single-family homes with an attached garage. The important results are summarized below:

- It is possible to measure all the appropriate leakages with multiple configurations using a single blower-door. It can be done with an accuracy as good as 20 percent, but only if the proper configuration is used. The configuration most often used in the field is not optimal.
- Reduced uncertainty and more robust measurement options are possible when two blower-doors are used. Ideal configurations can reduce the uncertainty to 16 percent, but poor experimental design can also lead to very poor results.
- Use of a single pressure station (e.g., 50 Pa) generally fails to produce reasonable results. It is possible to get acceptable results with a single-pressure station in special cases and when the relative leakage values are known in advance.
- From limited field measurements it appears the house-garage leakage is small by a significant fraction (e.g., 15 percent) of the total house leakage.

6.1.2.3 Energy Benefits of Air Sealing

By applying our simplified ventilation-energy model to the California housing stock it was possible to determine the impact that tightening programs would have and where the optimum level may likely to be. The analysis showed a clear trend with diminishing returns for more extreme tightness levels (i.e., $ACH_{50} < 1.5$) (or, equivalently, a California SLA of 3), which is likely to cost more to achieve. The exact optimum is different for each climate and cost structure, but it is clear that the stock could be profitably tightened. The extreme tightness required for the passive house is unlikely to be cost-effective. A practical rule of thumb is that the current stock could be profitably tightened to the level of the best 10 percent of the stock.

6.1.3 Indoor Contaminants

6.1.3.1 Prioritizing Contaminants for Health-Based Ventilation Standards

One of the most significant outputs of the RESAVE program is the prioritized listing of chronic indoor contaminants of concern. The study results showed that fine particulate ($PM_{2.5}$) has the most significant chronic health impact even in non-smoking households. In such households, formaldehyde is the next most important indoor contaminant. Following that are the products of combustion taken as a whole, with the chemical acrolein being the most significant. Ozone and radon can be important, but will be limited by the locations for which the outdoor ozone levels are high or where there is radon in the soil. These results were obtained by developing an

approach which converts exposures to Disability Adjusted Life Years (DALYs), which in turn can be monetized and compared with related costs and benefits.

6.1.3.2 Ventilation Control of Formaldehyde

Emission from materials is often the most important formaldehyde source within the home. Our analysis of concentrations has shown that these emissions vary with a variety of environmental parameters and most importantly with air change rate. Because emission varies with air change rate, ventilation is not as effective at reducing short-term formaldehyde concentrations as it is for more generic contaminants. It can, however, be as effective at reducing long-term exposures because a higher air change rate depletes the formaldehyde in the stored material faster.

By applying the DALY approach to formaldehyde control, this study found that even if the reduced effectiveness of ventilation is considered, reducing the long-term exposure of formaldehyde using ventilation can be cost effective. Of course, it may be even more cost effective to eliminate the source in the first place by not having materials that emit formaldehyde.

6.1.3.3 Source Control for Cooking Burners

Because particles and products of combustion have been identified as the most important indoor contaminants, cooking is the single most important source related to occupant activity. Unvented or poorly vented cooking appliances are thus substantial health hazards. Use of a range hood to capture these contaminants can substantially reduce these hazards. Our analysis shows that even a conventional range hood *can* reduce the fraction of time concentrations by 70 percent, but most range hoods perform substantially worse than that because they are not well utilized.

6.1.4 Optimized Ventilation

6.1.4.1 Optimized Mechanical Ventilation

Standard mechanical ventilation systems involve a constantly operating (or cycling) fan to provide continual ventilation regardless of the time of day or operation of exogenous ventilation systems. This study's simulations showed that by applying a smart control algorithm to any of the standard ventilation approaches, one can save 30 to 50 percent of the energy required for ventilation.

Such smart algorithms also allow a substantial reduction of demand by shifting ventilation away from peak period. They also allow a reduction of outdoor pollutants that are brought inside during periods when outdoor air quality is poor or, in principle, when the space is unoccupied.

6.1.4.2 Sustainable Ventilation

The most sustainable way to ventilate is without a fan at all. Many parts of the world use passive or hybrid ventilation strategies, which could be useful in a mild climate like California, but these have not been adopted. This study used simulation tools and the equivalent

ventilation approach to determine if using sustainable ventilation approaches make sense in California. The results show that passive and hybrid approaches can perform nearly as well as traditional mechanical approaches. For them to perform well, they must be well designed, and include some flow control products to minimize over-ventilation.

6.1.4.3 Ventilation Commissioning

A thorough review of the literature shows that commissioning of residential ventilation systems is not a common practice in California, but is being adopted in other countries. It also found that the literature is relatively devoid of field-test-related information that can be used in isolation to commission residential ventilation systems. When appropriate diagnostic methods were used, this study's field results showed that many systems being installed (e.g., almost half of the bathroom exhaust fans) do not meet the intended requirements.

Energy and IAQ simulation and DALY approaches were used to determine the value of residential ventilation system commissioning. We concluded that adjusting system airflows will always be of value in homes with low emission rates, as long as the price of tuning is less than the 30-year health and energy cost of an over-ventilating system. Our simulation results also suggest that controlling and limiting the levels of continuous emissions may be an important tuning tool for residential ventilation systems (i.e. if sources of a pollutant are removed, the ventilation rate can potentially be reduced). An interesting result of our simulations is that the economic optimum ventilation rate may be well above the current requirements of ASHRAE Standard 62.2, especially for homes with elevated emission rates.

6.1.4.4 Airflow Diagnostics

This study showed that there is great diversity in the performance of different products that contractors might use to measure airflow in ventilation-related systems for California homes. Some of this diversity is logistical because it can be practically impossible to attach an airflow measurement system to certain appliances (e.g., range hoods). Even when connection of the airflow diagnostic system is not an issue, different types of equipment may perform poorly because of insertion losses and asymmetric airflow. The study found, for example, that unpowered flow hoods are not very reliable for measuring outlet flows. In general, powered flow hoods were the most robust class of air-flow diagnostic equipment.

6.2 Benefits to California

As California seeks to reduce the environmental impact of homes while protecting the indoor environment, it must improve the energy efficiency of homes, and tightening homes to reduce infiltration is a straightforward means of doing so. The amount of energy saved depends on both the home's baseline energy use and what must be done to mitigate any negative impacts from tightening. Air sealing and tightening of the building envelope reduces air infiltration and its attendant energy costs in California homes, but doing so also reduces the total air exchange with outdoor air. California currently requires that new construction comply with ASHRAE Standard 62.2 to provide sufficient ventilation, but ASHRAE 62.2 is not an energy standard, and therefore allows many means of compliance which may not be optimal for energy efficiency.

6.2.1 Title 24 and ASHRAE Standard 62.2

California Title 24 is a key means for the State to implement energy efficiency in buildings. Because Title 24 references ASHRAE Standard 62.2, the RESAVE team has been very active in advancing this standard to improve its ability to provide acceptable IAQ while allowing the flexibility to do so energy-efficiently. A key benefit to California residents from the adoption and continued improvements in ASHRAE 62.2 is the improved health that goes along with improved IAQ, which can result in better school attendance and less productivity lost to IAQ-related illness. The 2013 version of Title 24 will reference most of the 2013 version of ASHRAE Standard 62.2. The RESAVE team has worked with ASHRAE to improve the version that will be adopted by California, and the team had several improvements implemented. Some of those that benefit California are listed below.

6.2.1.1 Equivalent Ventilation

Equivalent ventilation is the general principle that enables innovative ventilation systems to be shown as equivalent to the continuous ventilation specified in the standard. This enabling principle would allow the Energy Commission to determine if some future proposed ventilation technologies (such as the passive ventilation technologies investigated in RESAVE) comply.

While the general principle of equivalent ventilation is not yet operationally defined for the general case, there are two special cases that are explicitly described in the standard: one that looks at the impact of intermittent ventilation and one that looks at the impact of air leakage.

6.2.1.2 Intermittent Ventilation

One may wish to cycle a fan because outdoor air is undesirable at certain times, either because of the cost to condition or because it is contaminated (e.g., with high ozone concentrations). One may also wish to decrease the ventilation and attendant load during peak utility demand periods or when utility prices (or TDV) are high. The simplest way to cycle a fan is on a timer.

The intermittent ventilation approach of Standard 62.2 specifies how a ventilation fan may be cycled to be considered equivalent. A cycled fan, must be larger in capacity than a minimally compliant continuous fan, and overall will exchange more air per day, but it may result in less energy consumption and peak demand to do so.

6.2.1.3 Air Leakage Credit

Air leakage causes infiltration, which contributes to the home's overall ventilation rate. An airtight home requires more mechanical ventilation than a leaky one to achieve the same indoor air quality. The mechanical ventilation rate may be adjusted downward to account for air leakage, but that air leakage must be measured (using a blower door). California already requires a certain level of air-tightness testing, and that measured value may be used to reduce the energy needed for mechanical ventilation.

The ASHRAE 62.2-2013 version will not assume any default level of air leakage, but the California 2013 version will have a default infiltration credit. Either way, it is expected that adoption of 62.2-2013 will lead to many more homes being diagnostically tested for air leakage,

and this represents a significant advance in quality assurance and control procedures for California housing that will benefit Californians. It will also lead to better quality construction—representing a long-term investment in California's infrastructure and allowing the California construction industry to become national leaders.

6.2.1.4 Existing Buildings

Understanding California's need to reduce energy by retrofitting existing homes, the RESAVE team was instrumental in updating the 2010 version of ASHRAE Standard 62.2 (which was principally focused on new construction) to accommodate the practical issues associated with existing homes. The current version of 62.2 has an existing buildings appendix and additional requirements that enable it to be used for both deep and conventional retrofit applications.

6.2.1.5 Multifamily Buildings

ASHRAE Standard 62.2 is principally focused on single-family homes, but it has been updated for use in multifamily buildings.

6.2.2 Envelope Air Leakage

6.2.2.1 Residential Diagnostics Database

The air leakage database work benefits California in several ways: The analyses performed for the study help policy and other decisions makers to prioritize targets of opportunity by characterizing the stock of target homes in California that would benefit the most from air-tightening of the building envelope. These data can be used in simulation or forecasting models to determine the likely outcome energy savings of different programmatic air-tightening targets. Additionally the online database, http://resdb.lbl.gov, enables anyone from homeowners to policy makers to analyze envelope leakage for any subset of California homes that interests them. Finally, the data from this study's leakage database is being included in U.S. DOE's Home Energy Saver (http://hes.lbl.gov). Thus, when Californians use any of the Home Energy Saver suite of tools, they will benefit from the best information on air-tightness.

6.2.2.2 Multizone Leakage

The ability to make multizone leakage measurements is not yet a standardized process. It is far more complicated than a standard blower-door test, but as the need to address house-garage leakage or leakage among apartments in multifamily buildings grows in California, the need for such techniques grows. While the techniques evaluated or developed by RESAVE are not yet ready for widespread use in California, they are suitable for expert and research community use. Such use could lead to standardized test methods needed in retrofit and new construction programs.

6.2.2.3 Energy Benefits of Air Sealing

The ability to have a simplified physical model to predict the energy impacts of air sealing allows population-level simulation and forecasting to be done on the impacts of programmatic or policy-level decisions. In particular, this work has shown that there is likely an optimal air-

tightness level for California climates that balances the energy savings, cost to tighten, and negative operational consequences of very tight envelopes. More work is needed to refine this estimate, but it is likely in the vicinity of 2 ACH_{50} (or a California SLA of 1), with variations by climate.

6.2.3 Contaminants and Their Control

6.2.3.1 Prioritizing Contaminants for Health-Based Ventilation Standards

Having a prioritized list of contaminants of concern allows researcher and policy makers to focus their resources on key contaminants. This impacts the health of Californians, but it also supports the design of programs that can save energy while improving health. In the longer term, this prioritization has the potential to put the IAQ aspects of Title 24 and other standards on a health basis, rather than just a ventilation basis. This will most likely be done by working to modify the next version of ASHRAE Standard 62.2.

6.2.3.2 Ventilation Control of Formaldehyde

Formaldehyde levels exceed California standards in most homes around the State, but as the DALY approach has shown, it is not the most important contaminant indoors. While source control is the preferred option and is being pursued in California, ventilation is still a cost-effective strategy for reducing formaldehyde exposure. Our results suggest that it would be beneficial to improve California standards for not only formaldehyde exposure but also for testing and rating of formaldehyde-emitting products.

6.2.3.3 Source Control for Cooking Burners

This study's results indicate that well-designed range hoods with adequate flow rates can effectively remove cooking-related pollutants before they mix into the home. Widespread use of even moderately effective hoods would dramatically reduce pollutant exposures in California households. Energy-efficient control of IAQ requires that more emphasis be placed on this source. The area of ventilation controls should be considered in future energy and IAQ standards in California. For example: requiring that range hoods operate automatically or that all local exhaust fans operate at a low level even when "off" and can be turned to higher air flows by occupants when necessary. Some aspects of this were observed already in the new homes that were part of the ventilation commissioning part of the RESAVE program, where the bathroom and laundry room exhaust fans were operated automatically by humidity sensors.

6.2.4 Ventilation Systems

6.2.4.1 Optimized Mechanical Ventilation

This study's results showed that it is possible to optimize important State policy objectives at reduced energy costs through smart control of ventilation. These objectives go beyond the minimum ventilation standards, include protection from outdoor contaminants, and reduce peak demand while saving 40 percent of ventilation energy. By adopting the new version of

ASHRAE Standard 62.2 in the next version of Title 24, the use of such optimized control technologies will be allowed in principle.

6.2.4.2 Sustainable Ventilation

RESAVE has shown that the use of sustainable ventilation can be very helpful in California homes, particularly in retrofit programs. It can sometimes be cost-prohibitive to install mechanical ventilation as part of a retrofit package. Passive ventilation can facilitate economic energy reductions while protecting the indoor environment if appropriate controls are used to prevent over-ventilation. By adopting the new version of ASHRAE Standard 62.2 in the next version of Title 24, the use of sustainable ventilation will be allowed in principle.

6.2.4.3 Ventilation Commissioning

This work demonstrates that it would benefit California to require commissioning of residential ventilation systems as part of a compliance program and as required by ASHRAE Standard 62.2. Uncommissioned systems should be presumed to work poorly compared to commissioned ones based on observations of ventilation fan actual versus required flow rates in homes as shown in Stratton 2012, and penalized severely in energy and IAQ standards. With respect to VOCs like formaldehyde, the current study results show that Californians would be better off increasing their ventilation rates above the minimum required by code, but care must be taken to control particle concentrations. This is only a preliminary result, and a more thorough analysis needs to consider ozone and particle impacts when the air change rate is increased.

6.2.4.4 Airflow Diagnostics

The laboratory and field work on airflow diagnostics has indicated that most California homes would be expected to meet the whole-house ventilation requirements, but many would not meet the local exhaust requirements.

Products available for measuring flows in the California market have a wide range of performance and cannot be counted on to meet manufacturer specifications in all the reasonable configurations typically found. Until suitable industry standards have been developed, we find that only powered flow hoods meet California needs for all residential airflow, and that some passive flow hoods may be adequate for bathroom exhaust flow measurements.

6.3 Recommendations

Based on the results from this study, the California Energy Commission should consider the following actions and investments.

6.3.1 Title 24 2013

The RESAVE program has shown several technologies to be valuable. Some of these technologies are allowed under ASHRAE Standard 62.2-2013, but are not described or not enabled in the 2013 version of Title 24. It would be advantageous to California to invest in some enabling work to facilitate innovation in the following areas:

- Advance ventilation control systems, such as RIVEC, are allowed in principle in Title 24, but there is insufficient description to determine compliance. In such cases, innovative designers will not be able to take advantage of this technology. We recommend that research be conducted to develop a usable protocol for determining compliance.
- Sustainable, and particularly passive, ventilation approaches would facilitate advanced retrofit. Similar to optimized mechanical systems that are allowed but not enabled, the equivalency principle of ASHRAE standard 62.2 does not describe how to do sustainable ventilation. Performance specifications need to be developed to determine how to show compliance for such systems

6.3.2 ASHRAE Standard 62.2-2016

In the future, Title 24 will likely reference the next version of ASHRAE Standard 62.2, which is nominally scheduled to be published in 2016. The Energy Commission should provide research and technical support to the committee to make sure that changes and evolutions of the standard meet California needs. This will be particularly important as California seeks to achieve the goal of zero energy homes.

We recommend that the Energy Commission (perhaps with appropriate co-funding from the California Air Resources Board, CARB) undertake some specific research that will advance State interests for inclusion in 62.2:

- Contribution of cooking to indoor air quality: It may be much more energy efficient to improve the extraction of cooking contaminants than to increase whole-house ventilation rates. Understanding this trade-off may allow reduction in whole-house rates if other requirements are met, and this could reduce costs. Research is necessary to understand this trade-off and to ascertain the role of the acute exposures. Technologies for controlling exposure to cooking contaminants automatically need to be demonstrated and evaluated.
- The most important indoor contaminant is fine particulate, and it has both indoor and outdoor sources. Technologies exist to remove it, and the industry is continuing to advance these technologies, but research is necessary to facilitate trading off improved particle filtration for air flows or other contaminant control. Practical methods for including particle filtration in a ventilation standard need to be developed and demonstrated.
- Formaldehyde is the compound that exceeds California chronic standards the most. Research is necessary to put the exceedances of this contaminant in context with other contaminants, to allow energy use to be optimized without harming indoor air quality. Methods need to be developed, demonstrated, or evaluated to cost-effectively reduce formaldehyde concentrations, including ventilation, source control, and air cleaning.

6.3.3 Consensus Test Methods

The RESAVE program has shown that there are innovative techniques for evaluating energy performance and IAQ, but that in many cases there are not appropriate test methods or

diagnostics that can be used in the field. For California programs, codes, or standards to be able to require or allow new techniques, appropriate test methods must be developed and made available.

To develop and demonstrate these test methods, some research is necessary, and standards development effort is required. We recommend that the Energy Commission, in conjunction with appropriate federal agencies (e.g., U.S. DOE), work with the appropriate industry or consensus body to develop the following test methods or diagnostics:

- Multizone Leakage Test Method: ASTM E779 is the industry standard for using a blower-door in a single zone. RESAVE demonstrated that test methods could be developed for making multizone measurements, such as those that would be needed in multifamily buildings or for determining leakage of attached garages in single-family homes. Research is needed to determine the optimal protocols and then to work with ASTM (or another appropriate organization) to develop the standard.
- Capture Efficiency: Currently range hoods are rated by their flow rate, but that is only an intermediate to the desired metric, which is capture efficiency. One cannot specify capture efficiency in a code or standard because there is no test method for it. RESAVE (and other Energy Commission projects) have demonstrated that there are good ways to measure capture efficiency. Expanded research is needed to refine these methods and then to work with an appropriate industry or consensus body to adopt a test method suitable for adopting in a code or standard.
- Airflow Diagnostics: As demonstrated in this study, flow hoods have quite a wide performance range. If commissioning or similar field verifications are to be done on California homes, it is necessary to have methods of certifying performance of the airflow diagnostic equipment that will be used. A test method suitable for determining field performance of these devices does not yet exist, and one needs to be developed.

6.3.4 Stock Characterization

The RESAVE program has improved our knowledge of the state of air-tightness, ventilation, and indoor air quality in California, but it has also exposed data gaps. To develop better programs and codes to cost effectively save energy and improve indoor air quality, it is necessary to understand the stock of homes better. Therefore, Energy Commission should undertake field data collection and research to address the following issues:

- Aging of Building Envelopes: The envelope air leakage data created by RESAVE characterizes the stock of homes and shows that older homes tend to be more leaky. The database does not have sufficient data to separate out the effect of aging (that is buildings getting leakier as they age) from improvements in construction over time. Such data are necessary to understand the persistence of air-tightness savings, as well as to design better programs. Addressing this issue requires additional data from homes that have repeated air leakage measurements over time.
- Duct Leakage: In building the envelope air leakage database, incidental data were collected on duct leakage in California homes, but no systematic effort was conducted to

disaggregate substantial or representative duct leakage data. Since duct leakage can reduce HVAC efficiencies substantially, it is as important, if not more important, to understand the trends in duct leakage as it is to understand envelope leakage.

- Contaminant Exposures and Sources: RESAVE identified the contaminants of concern in California homes, but it is not known how these contaminants are distributed in different regions, house types, and seasons. A tailored expansion of the California New Homes Study would allow a better understanding of that distribution.
- Compliance Methods and Performance: California houses built since 2009 are required to meet ventilation requirements. It is not known which compliance options have been chosen, nor whether the intent of the requirements was actually met.

6.3.5 Technology Development

RESAVE was not primarily focused on the development of new technology, but its research results indicate areas where future technology development could be productive.

- New air leakage testing approaches and equipment will be needed to measure leakage in more complex building systems. Additionally, quick, low-cost air leakage test methods would help to improve audits of existing houses.
- Innovative air-sealing systems need to be developed if California intends to substantially improve the energy efficiency of existing homes.
- Improved sensors for the contaminants of concern such as particles, formaldehyde, acrolein, and others are required to enable the transition from a ventilation rate basis of IAQ to a health basis.
- Low-cost, high-efficiency air cleaning equipment could be part of an energy-efficient IAQ control strategy, but outside of particle filtration none yet exist for the residential environment.
- Since cooking is typically the largest single indoor source of contaminants in a non-smoking household, improved range hoods and other cooking source control measures would facilitate improved IAQ and reduced energy costs.
- The principle of equivalence allows ventilation loads to be shifted in time or to vary with loads and activities. Further development of smart ventilation (and ultimately IAQ) controllers would enable both energy and peak power savings.
- Passive ventilation strategies, particularly in retrofit environments, have the potential to be a low-cost, moderate efficiency technology, but require further development for use in California.
- Low-cost, reasonably accurate commissioning diagnostic equipment (and associated test methods) need to be developed to be able to realize energy savings from commissioning.