Emerging Products

Residential Crawl Space and Attic Conditioning and Sealing Retrofits

ET14SCE1100 & DR14.07.00 Final Report

Prepared by:

Engineering Services / Emerging Products
Customer Programs & Services
Southern California Edison

July 2019

SOUTHERN CALIFORNIA EDISON

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Acknowledgements

Southern California Edison's (SCE) Emerging Products (EP) group is responsible for this project. It was developed as part of Southern California Edison's Emerging Technologies Program and Emerging Markets & Technologies under internal project numbers ET14SCE1100 & DR14.07.00. M. M. Valmiki, P.E., Akane Karasawa, P.E., and Antonio Corradini, P.E., with Alternative Energy Systems Consulting, Inc. (AESC) conducted this technology evaluation with overall guidance and management from Ron Kliewer, Jay Madden, Bach Tsan, and Jerine Ahmed. Contact Bach.Tsan@sce.com or more information on this project.

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EXECUTIVE SUMMARY

A field assessment at four existing residential sites was conducted over three years to study the effects and implications of sealed, conditioned crawl space and attic retrofits. The findings can help determine which programs and stakeholders would need to be involved in future efforts, market transformation, or support roles. Energy usage, demand response, indoor air quality, market size, and market barriers were explored.

The measure under study is the sealing and conditioning of vented crawl spaces and attics in single-family residences. Sealed, conditioned crawl spaces and attics have vapor barriers, insulation on the exterior walls, and a pathway for conditioned air to circulate with the HVAC system and living space. The measure can improve building envelope air tightness, reduce duct leakage loads, reduce humidity levels, and improve overall air quality. It also has potential to improve demand response effectiveness by increasing available cool air and thermal inertia.

The field study data and analysis showed a variety of results. The highest savings were observed in the hottest climate zone and with ducting in the crawl space. Electrical energy savings of 19-28% were observed for the crawl space sealing while gas savings showed mixed results. Electrical energy went up with attic sealing but gas usage decreased by 45% at the site with ductwork in the attic. Total net savings after both measures were 0-32% of electrical usage and 26-39% of gas usage. However, the sites should be considered separately since each had different measure designs, equipment, ducting locations, and climate zones. Savings for each measure is highly dependent on duct leakage and locations.

Electrical savings were well-distributed over the daytime in the summer and demand response tests showed reductions similar to existing DR programs. Comparisons between the crawl space and attic phases suggested that the additional thermal inertia and conditioned air may reduce unwanted indoor air temperature increases during a demand response event. Although outdoor air conditions were not identical across the demand response testing, the indoor air temperature increases were roughly 30-50% of what was observed before attic sealing.

Indoor air quality and humidity levels were improved in all cases. High humidity levels in the crawl spaces and attics that can lead to mold and rot were virtually eliminated. Additionally, carbon monoxide and radon levels in the home were confirmed to be largely unaffected by the measures and in no case were increased to unsafe levels.

The average measure costs were $8.70 per square foot for crawl space sealing and $6.70 per square foot for attic sealing but could likely be reduced with standardization and increased market adoption. The existing vented crawl space market size is approximately 1,387,700 and 441,600 homes in California and SCE service territory, respectively. The existing vented attic market size is approximately 2,650,100 and 8,030,600 homes in SCE territory and California, respectively. Of these that have central air, the estimated potential savings is on the order of 400 and 1,100 GWh/year for SCE and California, respectively, if the Fullerton and Desert Hot Springs sites are considered typical.

Recommendations for further measure support are a comprehensive modeling and sensitivity analysis of both measures. This will allow for additional study of the measure

under control of influential variables and building types. However, common building modeling software cannot model conditioned crawl spaces and a custom solution or software modification might be needed. Program support could include code enhancement study, packaged residential rebates or incentives, best practice guidelines, and outreach and training for contractors to help foster market adoption and availability. Older homes with central air and ducting in the crawl space or attic would be most appropriate for early adopters and should be targeted for best cost-effectiveness. Even more tailored targeting could focus on homes with return and supply ductwork in the same space (attic or crawl space).

TABLE-ES 1. SUMMARY OF ENERGY SAVINGS AND DEMAND REDUCTION (CRAWL SPACE SEALING)

	ANNUAL ELECTRICITY SAVINGS (KWH/YR)	ANNUAL GAS SAVINGS (THERM/YR)	AVG DEMAND RESPONSE REDUCTION (KW)
Packaged AC with Gas Heat and Crawl Space Ductwork – Desert Hot Springs	2,132.3 (28%)	55.7 (59%)	1.14
Split System with Attic Ductwork - Fullerton	828.0 (26%)	-17.4 (-10%)	0.95
Window Units - Pomona	64.1 (19%)	n/a	n/a

TABLE-ES 2. SUMMARY OF ENERGY SAVINGS AND DEMAND REDUCTION (CRAWL SPACE AND ATTIC SEALING)

	ANNUAL ELECTRICITY SAVINGS (KWH/YR)	ANNUAL GAS SAVINGS (THERM/YR)	AVG DEMAND RESPONSE REDUCTION (KW)
Packaged AC with Gas Heat and Crawl Space Ductwork – Desert Hot Springs	-8.5 (0%)	14.6 (26%)	0.98
Split System with Attic Ductwork - Fullerton	490.0 (16%)	71.1 (39%)	0.50
Window Units - Pomona	113.4 (32%)	n/a	n/a

ABBREVIATIONS AND ACRONYMS

ACH50	Air Changes per Hour at 50 Pascals
BTU	British Thermal Unit
CBECC-Res	California Building Energy Code Compliance – Residential (software)
CCS	Conditioned Crawl Space
CDD	Cooling Degree Day
cfm	Cubic Feet per Minute
CO	Carbon Monoxide
CZ	Climate Zone
DR	Demand Response
HDD	Heating Degree Day
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
IAT	Indoor Air Temperature
kWh	Kilowatt-hour
OARH	Outside Air Relative Humidity
OAT	Outside Air Temperature
pCi/L	Picocurie per Liter
PCT	Programmable Communicating Thermostat
ppm	Part per Million
RH	Relative Humidity
SCE	Southern California Edison
SFR	Single-Family Residence
TDV	Time-Dependent Valuation

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INTRODUCTION

This is the final report documenting the results and conclusions of a three-year study of sealing crawl spaces and attics in four existing residential buildings in Southern California Edison (SCE) territory. After a period of baseline data collection on the existing single-family residences (SFR), the crawl spaces were sealed and conditioned followed by one year of data collection. The first report titled Residential Crawl Space Conditioning and Sealing Retrofits documented the experimental design, data, results of the crawl space measure, market size, and recommendations (Southern California Edison, 2018). This previous report provides much of the background and information on the experimental design relevant to both the crawl space and attic phases.

After a year of data collection with the sealed, conditioned crawl spaces, a similar measure was implemented on the attics prior to another year of data collection. Since the experimental design, measurement protocols, and analysis of the attic phase are identical to the crawl space phase, this report will not reiterate all of the details contained in the first report but serves as the standalone, final report for both measures. The three phases of the project are referred to as baseline (existing conditions), sealed crawl space phase (first measure), and sealed attic phase (second measure).

EXISTING CONDITIONS

Residential heating, ventilation, and air conditioning energy usage is affected by variables such as occupant comfort preferences and behavior, equipment specifications, maintenance, weather, and building characteristics. Building characteristics include factors such as thermal resistance, air leakage, duct design, and other construction features. In general, as houses age and degrade, energy consumption tends to increase. For instance, building leakage typically gets worse over time without corrective action and HVAC energy increases, compounded by aging equipment. Thus, retrofits on older homes can often save more energy than in new homes - although this sometimes comes with added measure complexity and cost of implementation.

Crawls spaces and attics can be categorized as conditioned or unconditioned and vented or unvented (sealed). Unconditioned implies no air transfer between the space and the HVAC system or living space and typically includes passive ventilation with outside air. Unconditioned spaces may have insulation under the living space floor or in the attic (e.g. batts or loose fill). Conditioned, sealed spaces have no venting to the outside and instead have vapor barriers, insulated exterior walls, and passive or forced air circulation with the HVAC system or living space.

FIGURE 1 - UNCONDITIONED, VENDED CRAWL SPACE AND ATTIC

Humidity and condensation are often cited as a concern with crawl space and attic sealing. Since moisture retention can cause structural and indoor air quality (IAQ) issues, this perception is a significant market barrier to adoption, especially in existing homes. Although historical thinking held that passive, outside venting is an effective and affordable method of managing moisture, it has been suggested that there is little compelling evidence along these lines (ASHRAE, 1994). In fact, vapor barriers and sealed spaces can be equally effective at moisture management and similarly cost-effective after accounting for insulation costs (ASHRAE, 1994), (Rose & Ten Wolde, 1994), (ASHRAE, 2017). This comes with the caveat that sealing attics and crawl spaces must follow best practices to allow ventilation and drying of spaces and materials outside the sealed envelope. For instance, air gaps between insulation and roofing layers may be necessary to prevent damaging condensation below the roof deck.

Additionally, there are energy implications to constructing vented, unconditioned crawl spaces and attics. Leaky ductwork located in these spaces can increase cooling energy costs by 15-30% (Yost, 2003) (Roberts & Winkler, 2010). Furthermore, sealing can not only contain duct leakage within the conditioned space, it may also reduce overall building tightness in older homes if implemented properly.

To summarize, issues that can arise from vented, unconditioned crawl spaces and attics include:

- Increased living space air leakage, exfiltration, and infiltration through the crawl space and attic.
- Increased loads from leaky ducts in unconditioned, vented spaces.
- High moisture, dry rot, and mold potential driven by moisture in earth and condensation.
- Stack effect and envelope infiltration increasing heating and cooling loads.
- Vermin and insect ingresses.

MARKET SIZE

According to the 2015 US Census, there are approximately 13,845,790 housing units in California, 58% of which are detached SFR buildings (US Census Bureau). Across the counties in SCE service territory, about 56% of the homes are detached SFR buildings. Additionally, SCE's customer base accounts for about 33% of all California electric customers (California Energy Commission, 2014). Since 23% of California SFR homes have crawl spaces and 75% of those are vented, the market size for this measure is approximately 441,600 buildings in SCE service territory and 1,387,700 buildings in California (US Census Bureau, 2017) (Chan, 2012).

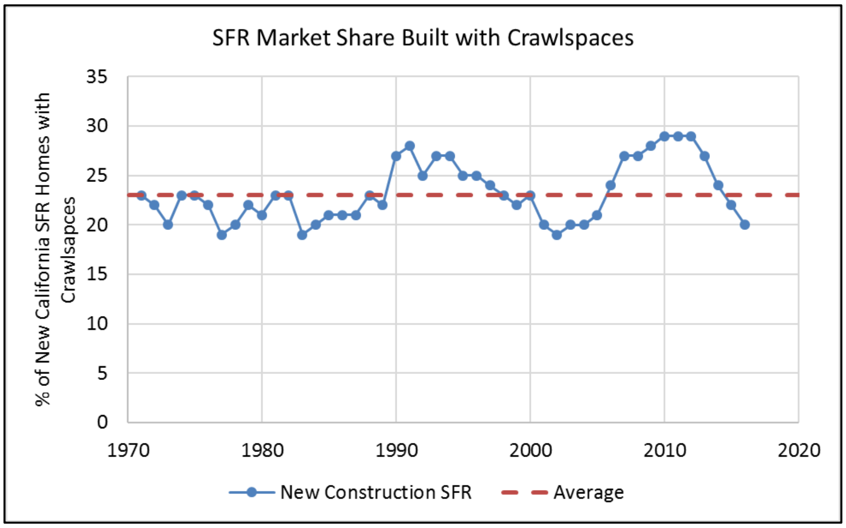

FIGURE 2 - CALIFORNIA SFR MARKET SHARE BUILT WITH CRAWL SPACES (US CENSUS BUREAU, 2017)

Across the United States, there are about 26 million existing homes with vented crawl spaces (Malkin-Weber, 2008).

The existing literature does not have substantial information on market penetration of sealed, conditioned attics. However, since nearly all homes have attics and standard practice has long been vented attics, it is reasonable to assume that nearly 100% of homes built before 2016 are candidates for the measure. It was estimated that only 100,000 homes with sealed attics were constructed between 1995 and 2007 in the entire United States (Schumacher, 2007). This is less than 1% of total new homes built in that time period. In California, 2016 Title 24 code changes shifted standard design practices towards sealed and high-performance attics, so newer vintages likely have less widespread opportunity.

TABLE 3 – ESTIMATED EXISTING MARKET SIZE OF VENTED, UNCONDITIONED CRAWL SPACES AND ATTICS (DETACHED SFR BUILDINGS)

	CRAWL SPACE MEASURE MARKET SIZE (HOUSING UNITS)	ATTIC MEASURE MARKET SIZE (HOUSING UNITS)
California	1,387,700	8,030,600
SCE Service Territory	441,600	2,650,100

However, the ideal target market is the subset of these homes with ductwork in one of the two unconditioned spaces. These buildings will yield the most energy savings from reduced duct leakage and heat exchange with unconditioned spaces. Existing data was insufficient to determine how many homes have ductwork in their crawl space or attic, but roughly 66% of SFR buildings will have central air in SCE service territory, and 56% statewide. It is reasonable to assume that nearly all of these will have ductwork in vented crawl spaces or attics.

EMERGING TECHNOLOGY BACKGROUND

CODES AND STANDARDS

Recent code changes have made progress towards increasing market adoption of sealed crawl spaces and attics. However, adoption rates of new construction sealed crawl spaces remain low and retrofits of existing home attics and crawl spaces are negligible (Lstiburek, 2004). The 2016 California Residential Code (Title 24, Part 2.5, Section R408) stipulates that crawl spaces can be vented or unvented. If a crawl space is unvented, exposed earthen floors must have a continuous vapor barrier and must be either mechanically ventilated or have a supply of conditioned air with a return to the living area at a rate of 1 ft^3/min per 50 ft^2 of floor area (California Building Standards Commission, 2016).

Additionally, the 2016 California Building Energy Efficiency Standards (Title 24, Part 6, Section 150.1(c)9) adopted prescriptive standards for high performance attics and ducts in conditioned spaces to improve efficiency of residences with ductwork in attics. As a result, new homes in climate zone (CZ) 4 and 8-16 are required to construct high performance attics, keep any ductwork in conditioned space, or implement alternatives with equivalent energy savings. High performance attics include insulation and duct tightness that yield savings equivalent to sealed attic construction. The originating Codes and Standards Enhancement Report determined that attic sealing was cost-effective for new homes with attic ductwork in CZ4 and CZ8-16 (California Utilities Codes and Standards Team, 2015).

LITERATURE SURVEY

Several studies have estimated the impacts of sealing crawl spaces. Generally, they showed that moisture management with sealed spaces is equally or more effective than vented spaces if properly implemented. These studies also have shown varying energy savings of 0%, 15-18%, and 32% (Hill, 1998), (Dastur & Davis, 2005), (Dastur, 2009), (Building Industry Research Alliance, 2007), (Biswas, 2011). However, these studies were largely concerned with new construction and were not necessarily equivalent to the conditions of this study. Due to differing conditions, the referenced studies should not necessarily be compared to the results of this one. Rather, the various results should together form a more comprehensive understanding of sealing and conditioning crawl spaces and attics.

Similar to the crawl space measure, savings estimates for attic sealing vary significantly depending on the conditions considered. A 1998 computational study estimated 4-9% energy savings from R-28 roof deck insulated sealing in Orlando and Las Vegas (Rudd & Lstiburek, 1998). Sealing of attics with ductwork has been shown to achieve savings of 6-20% of cooling energy and 0-25% of heating energy in new construction (California Utilities Codes and Standards Team, 2015), (Less, 2016). Attic sealing savings are highly dependent on duct leakage and are only significant with ductwork in the attic. A recent study of retrofit attic sealing in existing homes in Portland, Oregon combined building leakage measurements with building simulation to estimate savings of 71-105 therms per year in a heating-intensive climate (Research Into Action, 2015). A computational study of retrofit attic sealing estimated 22-28% savings in Austin, Baltimore, and Minneapolis with paybacks of 10-20 years (Miller, Desjarlais, & LaFrance, 2013).

EMERGING TECHNOLOGY DESCRIPTION

The retrofit measures in this field study comprise a combination of steps that create a sealed, conditioned crawl space or attic. The crawl space measure consisted of a vapor barrier that covers all crawl space ground and wall areas, closed cell spray foam sealing and insulation on the crawl space interior walls (~R-21), and conditioning by supplying an airflow path using transfer registers, ductwork, or fans. For instance, ductwork in the crawl space can be modified to have returns or supplies in the crawl space and vents in the floor can allow airflow between the crawl space and living space. The attic measure similarly consisted of a vapor barrier and R-21 closed cell foam.

FIGURE 3 - CRAWL SPACE VAPOR BARRIER AND ATTIC SEALING

Potential benefits of these measures may include:

- Reduced envelope leakage, infiltration, and exfiltration.
- More thermal mass available to smooth out interior temperature response to outside temperatures and enhance demand response (DR) potential.
- Improved insulation over existing baseline conditions.
- Reduced risk of dry rot, wood deformation, pests such as termites, standing water, and mold within the vapor barrier.
- Reduced duct leakage with unconditioned air, depending on duct location.

The construction measures had varying costs across the four sites due to their unique needs and HVAC equipment. Note that the Murrieta site's baseline included a crawl space that already had a vapor and moisture barrier on the soil floor (although it was not sealed or conditioned). As such, the Murrieta project costs were lower than the others. Table 4 and Table 5 list the total and per square foot costs for the crawl space measure.

TABLE 4 - CRAWL SPACE MEASURE COSTS

HOST SITE	INSULATION AND SEALING ($)	HVAC COST ($)	TOTAL MEASURE COST ($)
Desert Hot Springs	$6,917	$4,000	$10,917
Fullerton	$8,828	$2,300	$11,128
Murrieta	$4,320	$2,200	$6,520
Pomona	$8,071	$2,500	$10,571

TABLE 5 - CRAWL SPACE MEASURE COSTS PER SQUARE FOOT

HOST SITE	INSULATION AND SEALING ($/FT^2)	HVAC COST ($/FT^2)	TOTAL MEASURE COST ($/FT^2)
Desert Hot Springs	$7.69	$4.44	$12.13
Fullerton	$7.24	$1.89	$9.12
Murrieta	$2.88	$1.47	$4.35
Pomona	$6.96	$2.16	$9.11

Table 6 lists the total and per square foot measure costs for the attic measure. Note that the Murrieta site did not participate in the sealed attic phase.

TABLE 6 - ATTIC MEASURE COSTS

HOST SITE	INSULATION AND SEALING ($)	INSULATION AND SEALING ($/FT^2)
Desert Hot Springs	$5,643	$6.27
Fullerton	$7,662	$6.28
Pomona	$8,750	$7.54

ASSESSMENT OBJECTIVES

Since sealing and conditioning retrofits are not as well studied as in new construction, retrofit research was needed. Information from retrofit studies can help define future study directions and decisions on statewide and utility programs aligned with the measure. For instance, the measure may have a place in energy efficiency and DR programs of varying nature, building modeling software development, testing and certification methods, best practice guidelines, and otherwise. The findings can help determine which of these programs and their stakeholders will need to be involved in future efforts, measure development, market transformation, or support roles.

To that end, this study had several objectives:

- Measure energy usage and estimate savings of residential unvented, conditioned retrofit crawl spaces and attics.
- Perform DR tests to establish whether sealing measures improve residential HVAC DR effectiveness.
- Explore residential building and compliance whole building modeling and investigate the compatibility of existing software with conditioned crawl spaces and attics.
- Measure effects of crawl space and attic sealing measures on indoor air quality.
- Provide findings and recommendations for ET, EE program, DR program, and code readiness purposes.
- Provide data and analytical results in a field assessment report for public dissemination to increase understanding of the measures in a retrofit case.

To achieve these objectives, a field assessment at four existing residential sites was conducted over three years. The first year was for baseline monitoring while the second and third years were for retrofit measure monitoring (crawl space second year, attic third year).

TECHNICAL APPROACH/TEST METHODOLOGY

Since the research concerned retrofit applications of the measures, they were studied in the field at four existing SFR buildings across SCE service territory. Table 7 and Table 8 outline primary characteristics of the sites. The Murrieta site did not participate in the attic sealing measure phase.

TABLE 7 - HOST SITE OVERVIEW

HOST SITE	CA CZ	YEAR BUILT	BASELINE LEAKAGE[1] (ACH50)	LIVING SPACE AREA (FT^2)	BASELINE ENERGY INTENSITY[2] (KWH/FT^2-YR)	BASELINE ENERGY INTENSITY[3] ($THERM/FT^2$-YR)
Desert Hot Springs	15	1946	15.3	900	13.48	0.30
Fullerton	8	1957	13.2	1,220	5.07	0.22
Murrieta	10	1980	13.7	1,500 (1st floor) 940 (2nd floor)	4.33	n/a
Pomona	9	1920	37.6	1,160	7.36	n/a

TABLE 8 - HOST SITE CONSTRUCTION

HOST SITE	YEAR BUILT	CONSTRUCTION	ROOF	EXTERIOR DOORS	WINDOWS	WINDOW SHADING	WALL
Desert Hot Springs	1946	Wood frame: 2 x 4 wall studs, conventional rafter framing	Asphalt shingle	Solid wood	Single pane, wood frame, untinted	Blinds on all windows, closed during the day	R11 fiberglass batt
Fullerton	1957	Wood frame: 2 x 4 wall studs, conventional rafter framing	Asphalt shingle	Solid wood and dual pane glass patio slider	Double pane, vinyl frame, untinted	Blinds on most windows, open during the day	None
Murrieta	1980	Wood frame: 2 x 4 wall studs, conventional rafter framing	Asphalt shingle	Front door solid wood, back door wood with medium window	Mix of single- and double-pane, wood frame, untinted	No shading	R11 fiberglass batt
Pomona	1920	Wood frame: 2 x 4 wall studs, conventional rafter framing	Asphalt shingle	Front door solid wood, back door wood with medium window	Single pane, wood frame, one vinyl kitchen window	Curtains on most windows, closed during the day	None

The sites had higher energy use intensities than the average California home and average building air leakage, except for the Pomona site. The host sites were selected based on appropriateness for the retrofit measures, representativeness of typical existing residential

[1] Average envelope air leakage of California existing homes is about 14.6 ACH50 (Sherman & Dickeroff, 1998).

[2] Average energy intensities of California single-family homes are about 4.0 kWh/ft^2 and 0.22 $therms/ft^2$ for homes with gas service (KEMA, 2010).

[3] The Murrieta and Pomona sites do not have any natural gas heating.

building stock, and willingness to participate in an extended testing engagement. Since the test was invasive and extensive, participant willingness was a primary constraint in site recruitment. Due to the small sample size, the field assessment is meant to be a case study more than an analysis representative of market-wide potential or impacts, such as a building modeling assessment across prototype building conditions or a large population.

Table 9 outlines the baseline conditions and measures that were unique to each test site.

TABLE 9 - BASELINE AND MEASURE DETAILS

HOST SITE	HVAC SYSTEM	SYSTEM EQUIPMENT	BASELINE CRAWL SPACE	CRAWL SPACE MEASURE	BASELINE ATTIC	ATTIC MEASURE
Desert Hot Springs	Packaged unit with gas heat, ducted through crawlspace and floor registers. High occupied hours.	36,000 Btu/hr cooling, 13 SEER 60,000 Btu/hr heating, 80% AFUE 2 years old	Soil floor, vented, duct work, one exterior entry	10”x10” return duct in crawl space to draw when HVAC fan running. Floor register at house perimeter for airflow path between crawl space and living space. Vapor barriers and closed cell foam insulation, R12	Loose fill FG over R11 FG batts, ~R38 overall	Sealed with closed cell foam insulation, R38
Fullerton	Split system with gas heat, ducted through attic with ceiling registers	36,000 Btu/hr cooling, 13 SEER 80% AFUE 1 year old	Soil floor, one vented, exterior entry	8”x8” hole cut into close air handler return plenum, allowing air to be drawn from crawl space when HVAC fan in operation. Floor register at the four house corners foster air flow between living space and crawl space. Vapor barriers and closed cell foam insulation, R12	~R38 loose fill cellulose	Sealed with closed cell foam insulation, R38
Murrieta	(Lower Level) Package heat pump, ducted through crawl space with floor registers (Upper Level) Whole house fan and two window units	30,000 Btu/hr heat pump, 10 SEER, 6.8 HSPF 5,000 Btu/hr window units	Vapor barrier, duct work, vented, interior entry	10”x10” return duct in crawl space to draw when HVAC fan running. Floor register at house perimeter foster air flow between living space and crawl space. Vapor barriers and closed cell foam insulation, R12	~R19 FG batts between joists with some significant gaps	n/a
Pomona	Two window units in bedrooms, no heat, no ducts	9,000 and 7,000 Btu/hr, 9.7 EER	Soil floor, vented, three exterior entries	Floor register with flexible duct and fan installed in crawl space to force air into living space. Three floor register installed in three corners of house to foster air flow between living space and crawl space. Vapor barriers and closed cell foam insulation, R12	Small amount of loose fill and R19 batts with many uncovered joists and open spaces	Sealed with closed cell foam insulation, R38

The baseline data for existing conditions were collected for roughly three seasons, from May to February. One year of data was collected for each subsequent measure, a crawl space phase and an attic phase.

Instrumentation and data collection points were selected to gain a complete perspective of the building response to the measure in line with International Performance Monitoring and Verification Protocol Guidelines (IPMVP). Measurement points were selected to follow IPMVP Options B (Retrofit Isolation All Parameter Measurement) and C (Whole Facility). Under Option B, measurements are taken at all building parameters and energy consumption points that are necessary to establish normalized energy savings at the systems affected by the measures. Gas usage and savings were determined using Option C by using gas billing data instead of independent sub-system measurement. Additionally, several other data points were collected to confirm that the measures did not negatively affect IAQ and building health metrics.

The measurement points and instrumentation are listed in Table 10.

TABLE 10 - DATA COLLECTION POINTS AND INSTRUMENTATION OVERVIEW

MEASUREMENT	INSTRUMENTATION	LOGGING INTERVAL
Power monitoring (fans, condensers, compressors, package units, window units)	CTs with amperage data loggers, spot measurements of power factor and voltage	1 minute
Natural gas usage	Southern California Gas utility	Billing period
Temperature and relative humidity – indoor, outdoor, attic, and crawl space air	Onset HOBO sensors and data loggers	15 minutes
HDD and CDD	Local airport weather station	1 hour
Soil temperature	Onset HOBO sensors and data loggers	15 minutes
Carbon monoxide – indoor, outdoor, attic, and crawl space	Dwyer CO data logger	5 minutes
Indoor radon	Family Safety Products Safety Siren	Short and long-term averages

Although data was logged at intervals of 1, 5, and 15 minutes, the data was eventually consolidated to hourly and daily intervals. Analysis began at small intervals, but the response times of the building and the regression analysis required a longer interval to establish usable regression equations. At all sites, data was stored in onsite loggers and manually retrieved periodically (roughly every three months). While this did result in some data gaps due to monitoring malfunctions between data collection site visits, instrumentation was checked regularly for quality assurance.

Since the residential host sites were private and had to be treated sensitively, not all variables could be controlled. For instance, space temperature setpoints, occupied hours, HVAC scheduling, building maintenance, personal preferences, and other such variables were out of the experimental control. For tighter control of all relevant experimental variables and true measure isolation, unoccupied building or lab testing under controlled conditions would be required.

Data was used to establish energy usage relationships to independent weather variables. By establishing normalized energy usage relative to weather, energy usage before and after measure implementation can be compared. Non-weather dependent variables were also explored for normalization (such as weekday, season, and time of day), but only outdoor air temperature (OAT), heating and cooling degree days (HDD and CDD), and indoor air temperature (IAT) were found to be significant variables in the analysis.

To calculate normalized energy consumption, linear regression equations were established for each site. In general, these regression equations took the following form:

$$E = a + [b \cdot OAT] + [c \cdot OAT^2] + [d \cdot IAT] + [e \cdot (OAT - IAT)]$$

where E is daily HVAC electrical or natural gas energy, OAT is the outdoor air temperature, and IAT is the indoor air temperature. Although regressions with differing independent variables were tested for viability, not all variables were needed for each site. The regression coefficients and variables were ultimately selected based on simplicity, statistical significance, and accuracy. IAT was necessary in some cases where the indoor temperatures differed significantly between monitoring periods or when statistical significance could not be achieved with only OAT as an independent variable. Additionally, heating and cooling degree days were used in place of (OAT-IAT) for longer intervals or where HVAC use was infrequent, such as in the case of the Pomona site.

The regression equations were then used to estimate normalized annual energy usage. Outside air temperatures were averaged across three years of local weather station data so that an annual, localized weather pattern could be used for annualization. This was used in addition to CA CZ weather data because host site local weather was somewhat different from CZ representative datasets. Thus, normalized energy consumption and savings results were obtained using both local weather station data and CZ data are presented in this paper.

RESULTS

The baseline and post-retrofit energy use was compared for each site to ascertain the energy savings potential of the measures. Additionally, some IAQ parameters were measured and DR tests were performed in the measure cases (the baseline controls did not allow for DR testing). In all cases, comfort conditions improved in the living space. The inside air temperature and RH stayed closer to the typical comfort range over the observed range of outside air conditions. Additionally, radon and carbon monoxide levels were not adversely affected and stayed within safe bounds in both the baseline and post-measure cases. Humidity in the crawl space and attic improved in all cases and excessive levels that could lead to moisture problems were virtually eliminated. This can help reduce risk of structural degradation as long as proper ventilation of the roof deck is included in the installation.

Table 11 summarizes the energy savings achieved from the crawl space measure with the existing baseline normalized to local weather station data.

TABLE 11 – CRAWL SPACE MEASURE RESULTS WITH EXISTING BASELINE[4]

HOST SITE	ENVELOPE LEAKAGE REDUCTION AT 50 PA (CFM)	AVG DEMAND RESPONSE REDUCTION[5] (KW)	ELECTRICITY SAVINGS (KWH/YR)	NATURAL GAS SAVINGS (THERMS/YR)
Packaged AC with Gas Heat – Desert Hot Springs	280 (15%)	1.14 (60%)	2,132 (28%)	55 (59%)
Split System with Gas Heat – Fullerton	-605 (-28%)	0.95 (49%)	828 (26%)	-17 (-10%)
Supplemented Heat Pump – Murrieta	410 (8%)	n/a	0	n/a
Window Units - Pomona	73 (1%)	n/a	64 (19%)	n/a

[4] Negative values indicate usage or leakage increases.

[5] Average DR reduction for California SFR programs is about 1.09 kW (Southern California Edison, 2009).

Table 12 summarizes the energy savings achieved from the attic measure with the crawl space phase as baseline after normalized to local weather station data. Note that the Murrieta site did not participate in the attic sealing phase.

TABLE 12 - ATTIC MEASURE RESULTS WITH CRAWL SPACE PHASE AS BASELINE

HOST SITE	ENVELOPE LEAKAGE REDUCTION AT 50 PA (CFM)	AVG DEMAND RESPONSE REDUCTION (KW)	ELECTRICITY SAVINGS (KWH/YR)	NATURAL GAS SAVINGS (THERMS/YR)
Packaged AC with Gas Heat – Desert Hot Springs	265 (17%)	0.98 (40%)	-2,140 (-28%)	-31 (-81%)
Split System with Gas Heat – Fullerton	605 (22%)	0.50 (46%)	-337 (-15%)	88 (45%)
Window Units - Pomona	570 (10%)	n/a	49 (18%)	n/a

Table 13 summarizes the net savings achieved by both measures with the existing baseline (original homes). This data was normalized to local weather station data. Evidence suggests that the additional thermal inertia created by the sealing and insulating measures can help reduce the inside air temperature gains during DR setpoint adjustments. However, the DR reduction was less after attic conditioning.

TABLE 13 - NET RESULTS WITH EXISTING BASELINE

HOST SITE	ENVELOPE LEAKAGE REDUCTION AT 50 PA (CFM)	ELECTRICITY SAVINGS (KWH/YR)	NATURAL GAS SAVINGS (THERMS/YR)
Packaged AC with Gas Heat – Desert Hot Springs	545 (30%)	-8.5 (0%)	14.6 (26%)
Split System with Gas Heat – Fullerton	-5 (0%)	490 (16%)	71.1 (39%)
Window Units - Pomona	643 (11%)	113 (32%)	N/A

Additionally, savings were estimated for each building type across the studied locations using California CZ weather years.

CARBON MONOXIDE, HUMIDITY, AND RADON

One concern with reducing outside air ventilation is carbon monoxide (CO) levels in the living space, produced from fuel-burning appliances and equipment such as furnaces, water heaters, and stoves. Elevated levels of CO can be toxic and life-threatening. There are several recommended exposure limit standards by various agencies. There is no statewide code, except a mandate that new single-family residences have approved CO alarms installed. ASHRAE 62.2 recommends a long-term exposure limit of 9 ppm for indoor residences. In recent years, the EPA has reported background, metropolitan area CO levels of under 5 ppm in the southwest region that includes California (Environmental Protection Agency, 2013).

Figure 4 shows the measured daily average CO levels inside the Desert Hot Springs (DHS) residence over the baseline and measure periods. It is obvious that inside CO levels do not increase to unsafe levels due to the measure.

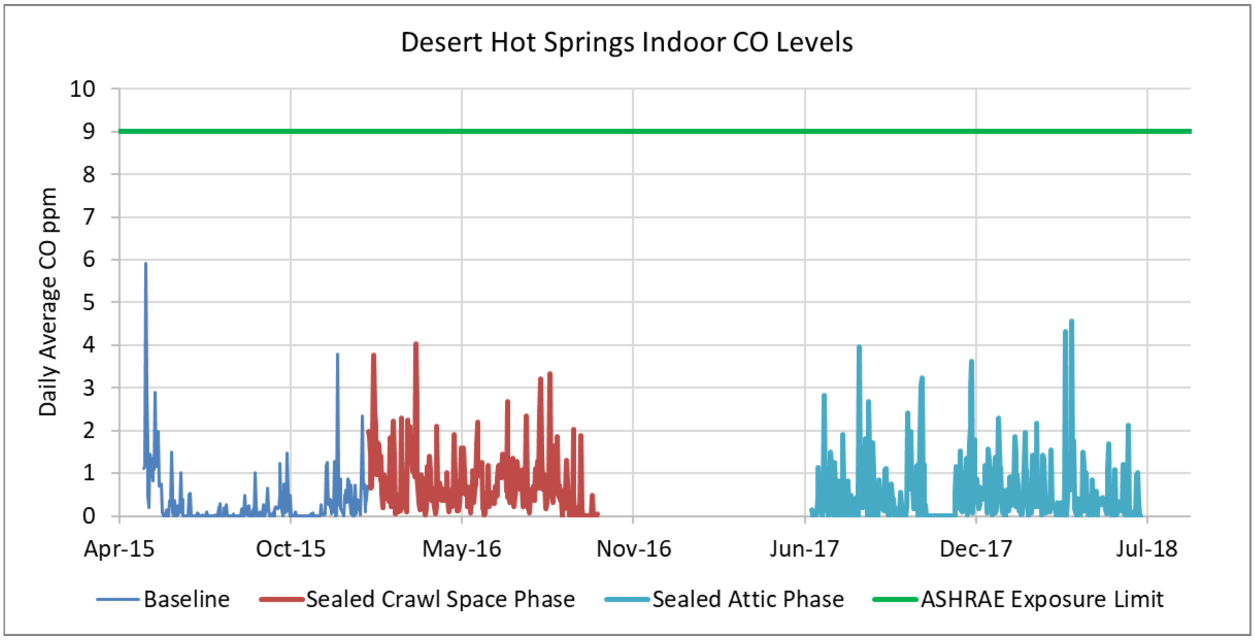

FIGURE 4 - DESERT HOT SPRINGS CARBON MONOXIDE MONITORING

Similarly, no significant increases or unsafe levels were apparent after the crawl spaces and attics in the other homes were sealed and conditioned. Figure 5, Figure 6, and Figure 7 show the indoor CO levels recorded for the other three sites before and after each measure. These figures support the conclusion that CO concentrations inside the living space were not negatively affected or increased to unsafe levels due to the measures.

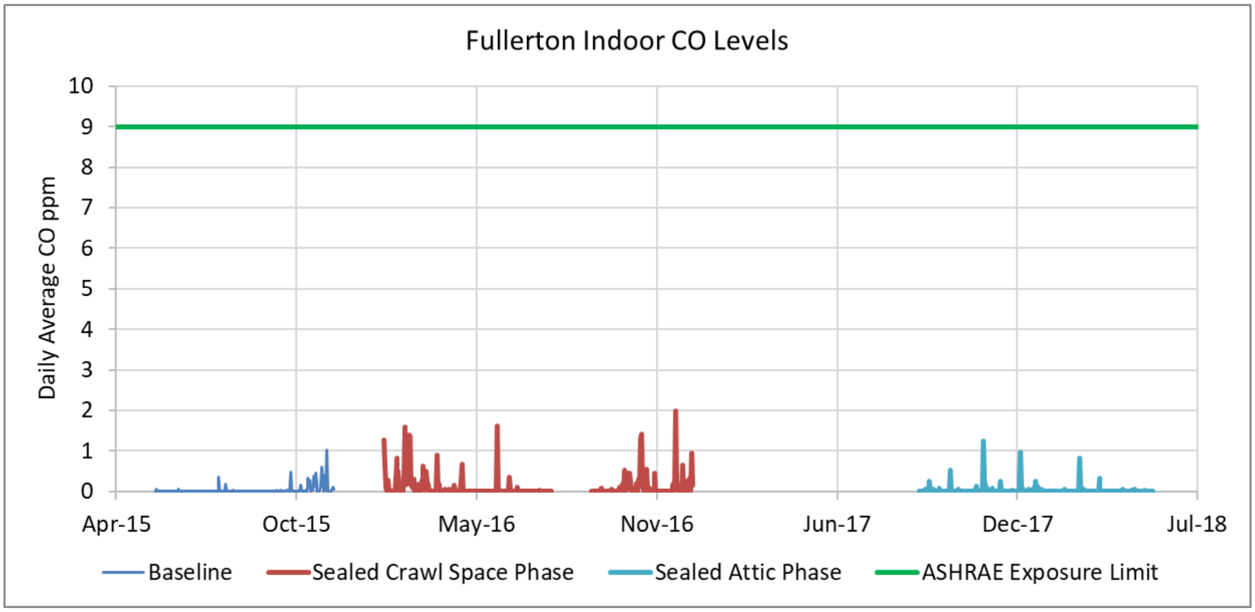

FIGURE 5 - FULLERTON CARBON MONOXIDE MONITORING

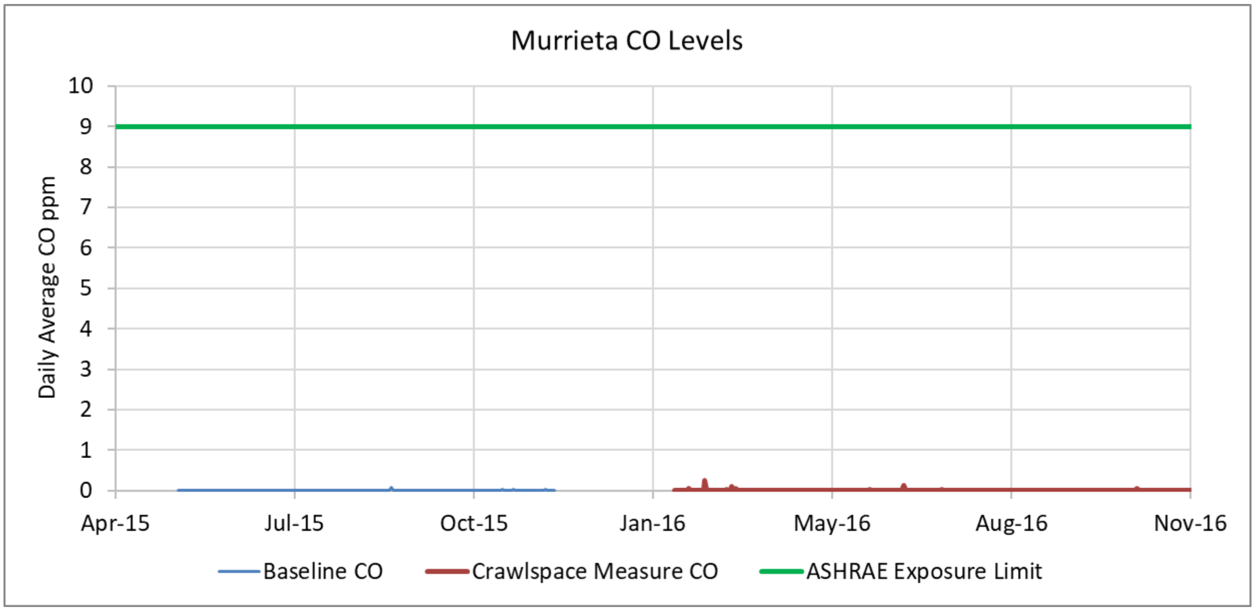

FIGURE 6 - MURRIETA CARBON MONOXIDE MONITORING

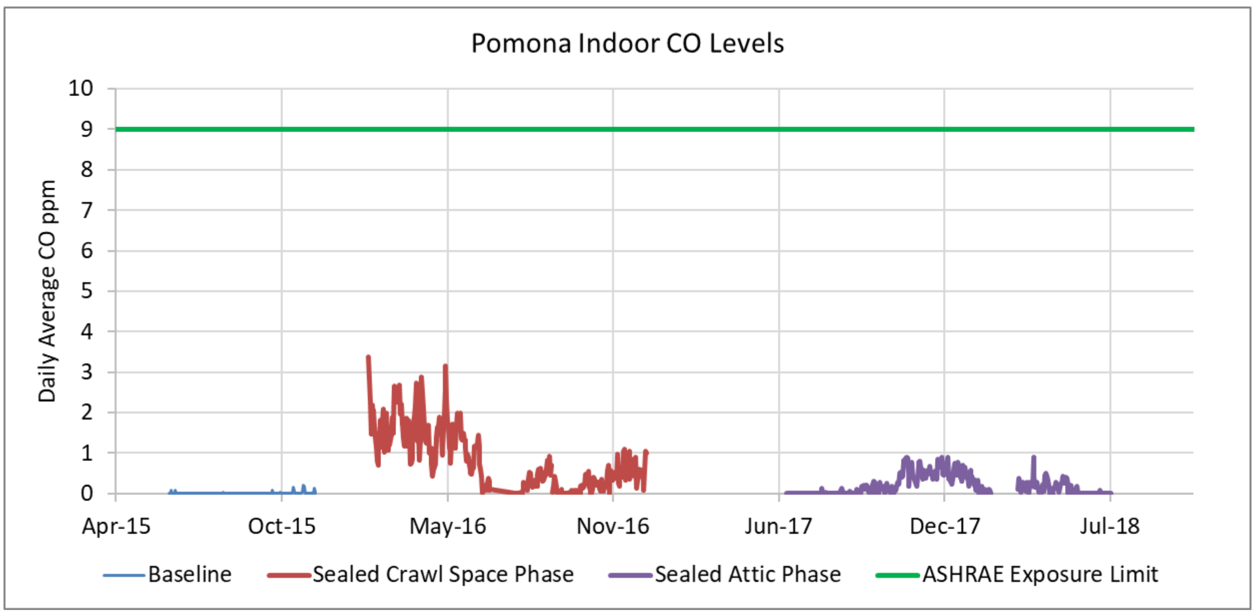

FIGURE 7 - POMONA CARBON MONOXIDE MONITORING

Another air quality and building integrity concern with crawl spaces is the buildup of moisture. This can occur due to a combination of poor ventilation and transfer of moisture from the soil and outside air into the building spaces, especially when there is a large temperature difference between day and night. It is typically recommended that RH levels be kept below 70% to avoid condensation and moisture buildup that can result in mold growth (EPA, 1991).

The reductions in slope from baseline to post-measure cases in Figure 8 and Figure 9 show that the crawl space and attic air humidity had less dependence on outside air conditions, meaning that less air infiltration resulted in lower humidity, generally. This is shown by the lower overall average crawl space and attic humidity in the post measure cases. This dispels the notion that sealing might trap moisture in the spaces after eliminating passive ventilation with the outside.

Although crawl space humidity increased at the lower end of the outdoor humidity range, the greater concern is at the higher values of RH. Sealing of the crawl spaces and attic showed reduced humidity at the higher end of the range for all sites. In fact, the baseline monitoring observed many days with average humidity above the threshold of 70% while the post-sealing periods had virtually no days with humidity above 70%. Thus, the measures are an obvious benefit in terms of moisture reduction and mold prevention and will keep humidity below recommended threshold limits.

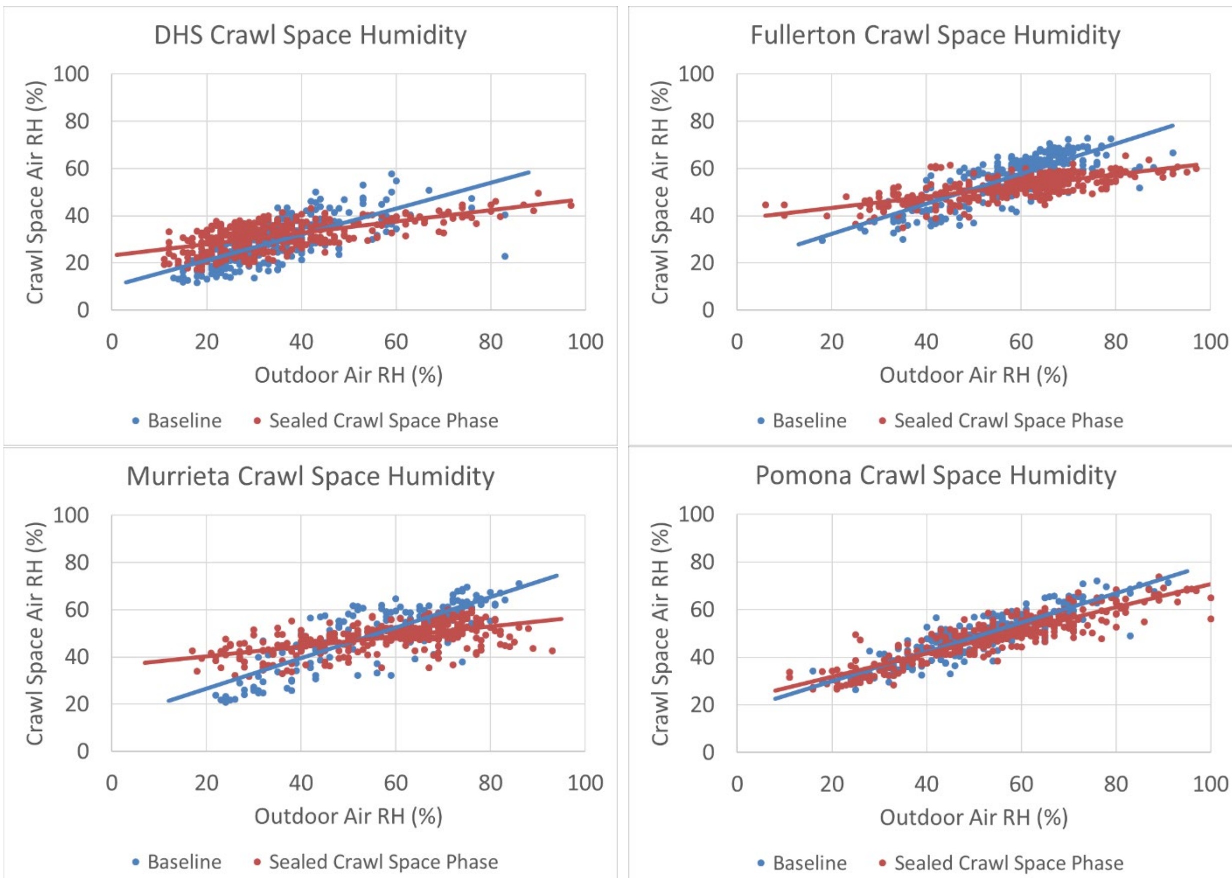

FIGURE 8 - CRAWL SPACE AIR HUMIDITY RELATIONSHIP TO OUTDOOR AIR

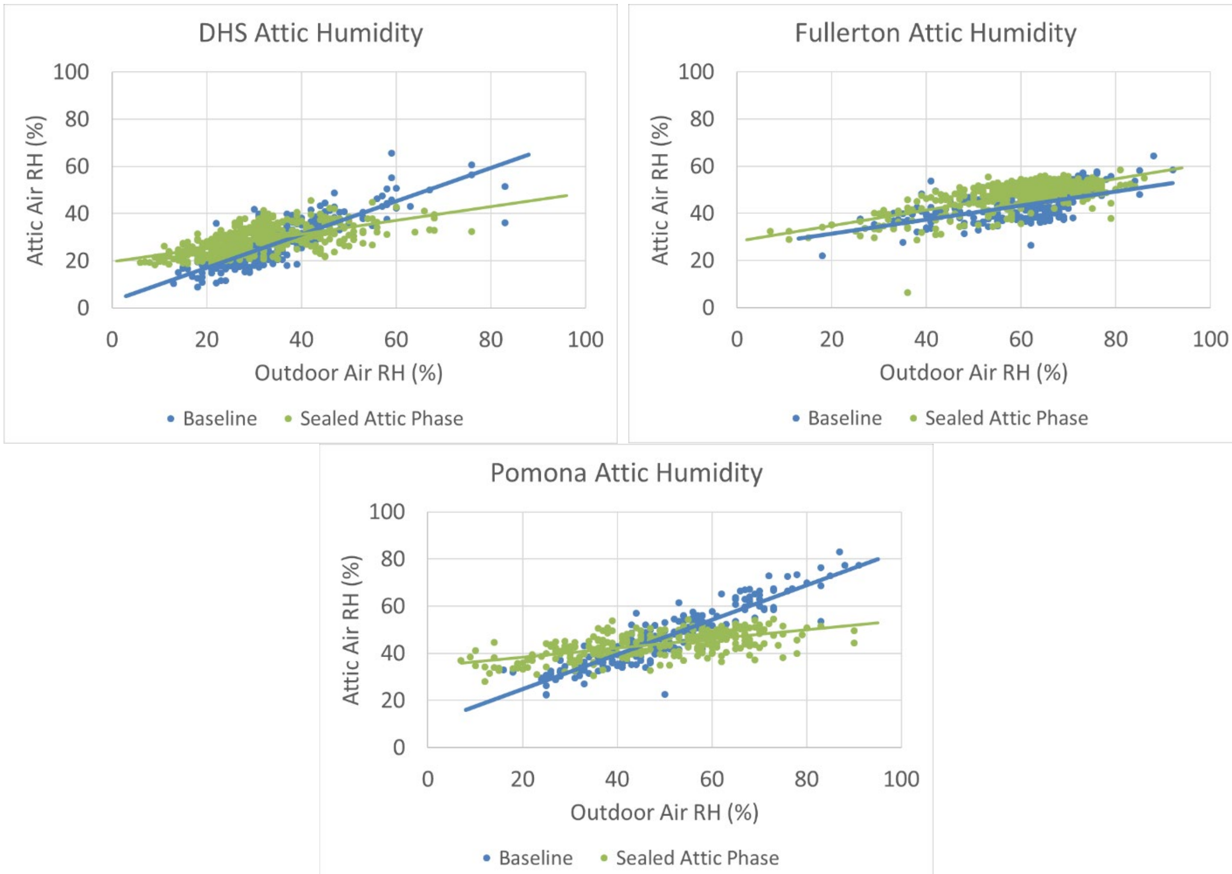

FIGURE 9 - ATTIC AIR HUMIDITY RELATIONSHIP TO OUTDOOR AIR

Table 14 and Table 15 further demonstrate the reduced crawl space and attic humidity effects. The total time spent above 70% relative humidity decreased progressively in both spaces across the measure implementation.

TABLE 14 - PERCENT TIME WITH CRAWL SPACE RELATIVE HUMIDITY ABOVE 70%

HOST SITE	BASELINE	SEALED CRAWL SPACE PHASE	SEALED ATTIC PHASE
Desert Hot Springs	0%	0%	0%
Fullerton	4%	0%	0%
Murrieta	1%	0%	n/a
Pomona	3%	1%	0%

TABLE 15 - PERCENT TIME WITH ATTIC RELATIVE HUMIDITY ABOVE 70%

HOST SITE	BASELINE	SEALED CRAWL SPACE PHASE	SEALED ATTIC PHASE
Desert Hot Springs	1%	1%	0%
Fullerton	6%	3%	0%
Murrieta	5%	2%	n/a
Pomona	12%	12%	0%

It should be noted that moisture levels in the roof deck and any crawlspace framing outside of the vapor barriers and insulation were not measured. Proper construction and installation techniques are necessary to allow the roof deck to dry out via space between the structural materials and the insulation and/or vapor barriers.

While high humidity levels in the crawl spaces and attics were largely eliminated, indoor air humidity was unaffected, thereby maintaining indoor air quality as seen in Figure 10.

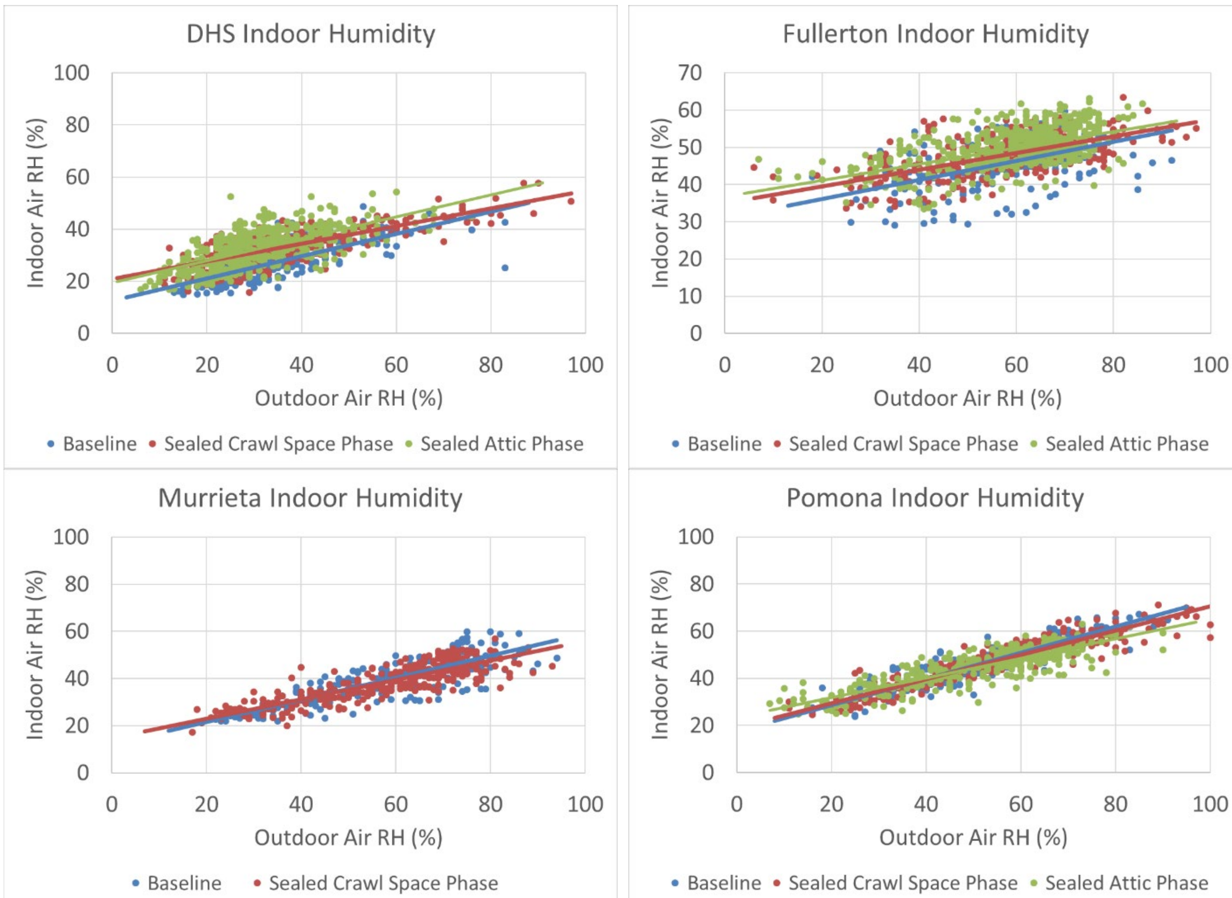

FIGURE 10 - INDOOR AIR HUMIDITY RELATIONSHIP TO OUTDOOR AIR

Another indoor health metric that needs to be observed is radon levels in the home. Radon, measured in pCi/L, can enter the house due to a release from soil and rocks at the foundation. Mitigation of high levels of radon often involves forced ventilation of crawl spaces. Thus, it is conceivable that sealing of crawl spaces could potentially affect the levels of radon entering and accumulating in the home. While vapor barriers can reduce radon entering the house, the absence of exterior ventilation could potentially increase radon concentrations.

Although there is no standard dictating safe levels of radon in the home, mitigation is typically recommended if levels are above 4 pCi/L (Environmental Protection Agency, 2012). Household alarms typically sound alerts when levels exceed that value.

Table 16 lists the recorded long-term average radon levels measured in the living spaces of each home. The data did not provide conclusive evidence on whether the sealing affected indoor radon levels positively or negatively. In all cases, however, the measures did not increase any sites radon readings above 4.0 and decreased the only site that saw baseline levels above recommended limits.

TABLE 16 - OBSERVED RADON LEVELS

HOST SITE	BASELINE RADON LEVEL (PCI/L)	SEALED CRAWL SPACE PHASE RADON LEVEL (PCI/L)	SEALED ATTIC PHASE RADON LEVEL (PCI/L)
Desert Hot Springs	0.8	1.8	1.4
Fullerton	1.7	2.6	3.4
Murrieta	1.2	1.3	n/a[6]
Pomona	5.5	4.6	2.6

PACKAGED AC WITH GAS HEAT – DESERT HOT SPRINGS

The Desert Hot Springs site is a 1946 single-story building with 900 square feet of living space, a 3-ton package unit with gas heat, ductwork in the crawl space, and no shade in CZ15. Blower door testing showed the building had envelope air leakage rates indicated in Table 17. The crawl space and attic sealing measures reduced air leakage by about 15% and 17%, demonstrating that there was a substantial reduction of building leakage with the outside. The crawl space was conditioned by adding a small return duct from the crawl space and three air transfer vents in the floor between the crawl space and living areas.

TABLE 17 - DHS BLOWER DOOR TESTS

	ENVELOPE LEAKAGE AT 50 PA (CFM)	LEAKAGE REDUCTION AT 50 PA (CFM)	ENVELOPE LEAKAGE (ACH50)	LEAKAGE REDUCTION (ACH50)
Baseline	1,840	-	15.3	-
Sealed Crawl Space	1,560	280 (15%)	13.0	2.3
Sealed Attic	1,295	265 (17%)	10.8	2.2

[6] Occupants removed radon meter.

As seen in Figure 11, the indoor temperatures do not follow the same trend during the baseline and measure periods. The figure shows that IAT was much cooler during the crawl space and attic measure periods, especially at higher ambient temperatures.

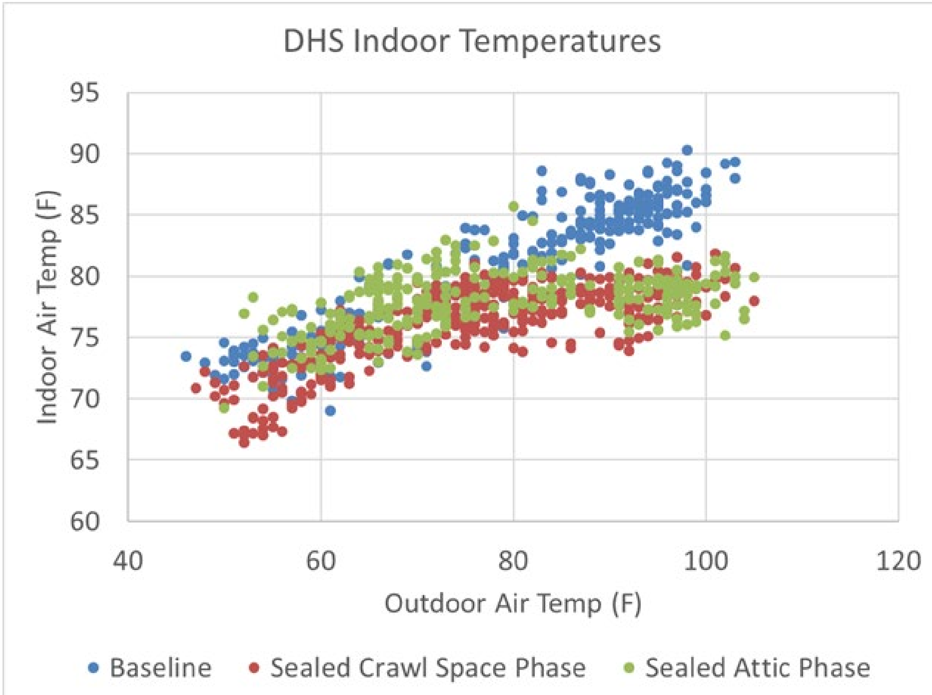

FIGURE 11 - DHS INDOOR AIR TEMPERATURES

Note that the IAT was measured close to the ceiling to remain inconspicuous. Thus, the values are useful for normalization and regression analysis, but do not necessarily represent exact temperatures felt by the occupants.

The difference in IAT after the measure implementation may be due to a few factors:

- Lower average outside air temperatures during crawl space measure period.
- Decreased loads on cooling system allowing system to meet loads that may have previously been too large for the system sizing.
- Changes in thermostat settings or behavior.

This decrease in indoor and outdoor air temperatures can also be seen in the psychrometric chart of daily average indoor air conditions in Figure 12. The indoor air data cluster contrasts significantly and comfort conditions improve.

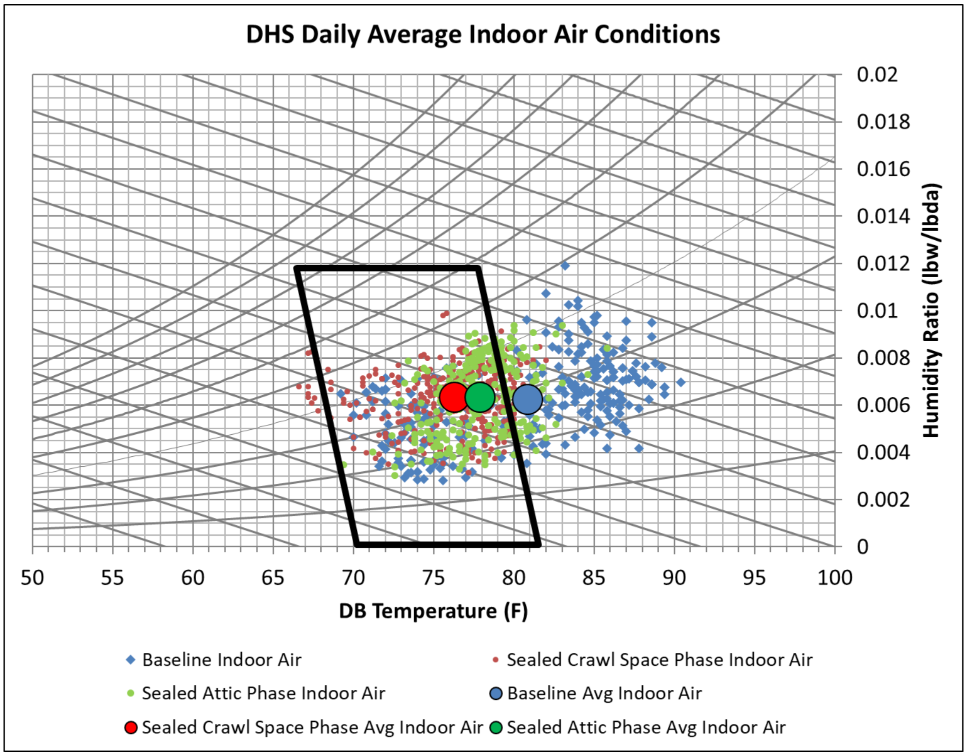

FIGURE 12 - DHS INDOOR AIR CONDITIONS (DAILY AVERAGES)

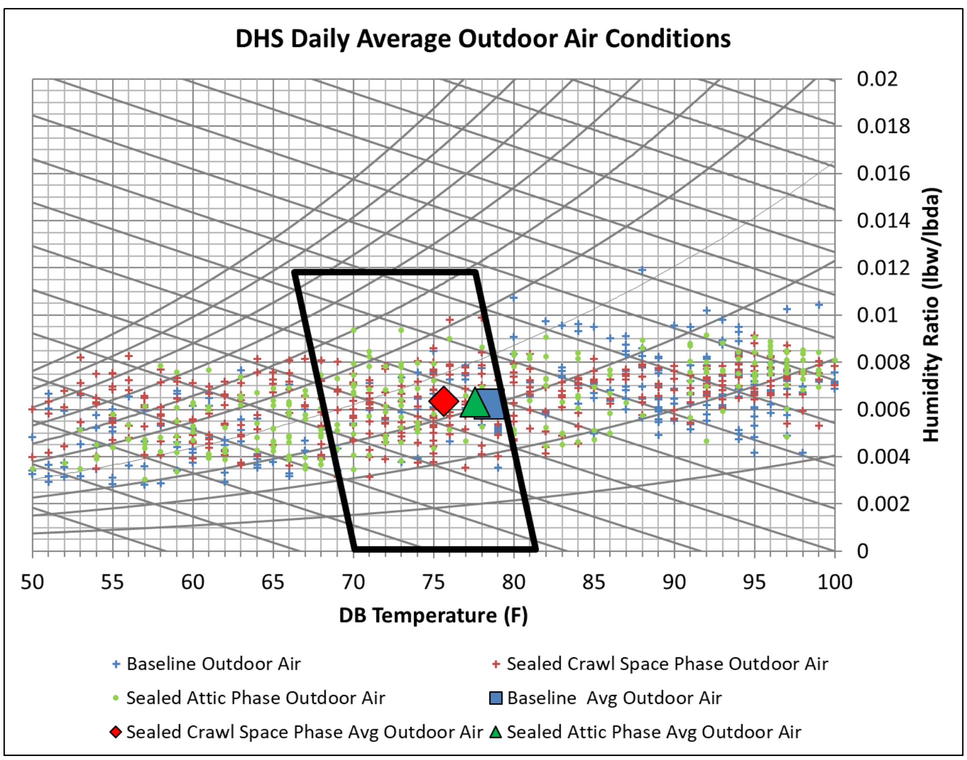

FIGURE 13 - DHS OUTDOOR AIR CONDITIONS (DAILY AVERAGES)

Normalization of energy use to outdoor and indoor air temperatures can account for these changes between the two periods. For the Desert Hot Springs site, electrical energy use was found to have the most robust relationship to the difference between inside and outside air conditions, (OAT – IAT). Note that OAT-IAT is similar in form to degree days; it is a variable that represents the cooling load of the building based on occupant preferences, OAT, and control settings. This choice of independent variables can account for the change in controls and potential occupant preference differences from the baseline to measure periods.

Figure 14 shows the regression relationship between daily energy consumption and average temperature difference across the envelope that was used for annualization of energy consumption.

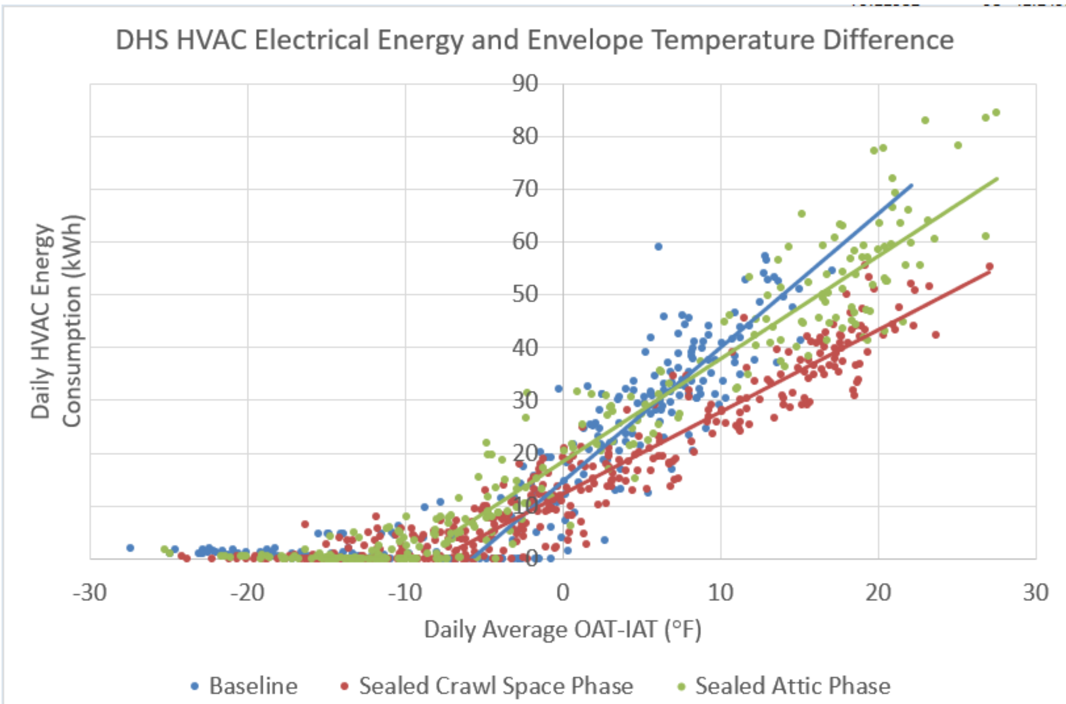

FIGURE 14 - DHS HVAC ENERGY RELATIONSHIP TO ENVELOPE TEMPERATURE DIFFERENCE

Linear regression models for electrical energy usage were established based on the data shown in Figure 14:

$$Daily\ kWh = \begin{cases} A & for\ all\ (OAT - IAT) < -7 \\ B + [C * (OAT - IAT)] & for\ all\ (OAT - IAT) \geq -7 \end{cases}$$

The electrical energy usage during cooler weather were averaged to obtain *A.* The linear regression coefficients used are listed in Table 18. Note that the changepoint is roughly equivalent to OAT of 72 F.

TABLE 18 - DHS DAILY ELECTRICAL ENERGY REGRESSIONS

	BASELINE	SEALED CRAWL SPACE PHASE	SEALED ATTIC PHASE
A	1.56	1.16	1.39
B	14.64	12.27	18.35
C	2.54	1.56	1.95
Regression R^2	0.80	0.90	0.88

Similarly, linear regressions for gas consumption can allow for normalized annual energy usage and savings estimates. Gas data was collected from billing statements, so the measurement intervals were about 30 days and were for the whole building rather than space heating only.

As shown in Figure 15, gas usage has a linear relationship to HDD60. The y-axis intercept where heating loads are negligible represents gas usage during the non-heating season for cooking and domestic hot water end-uses. This can be used to isolate space heating gas usage from the total usage.

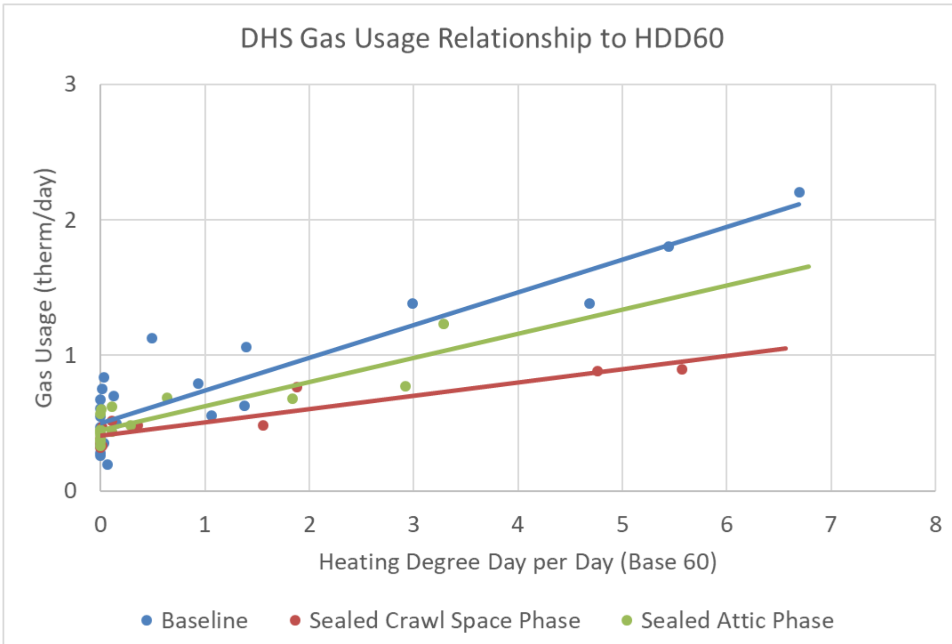

FIGURE 15 - DHS GAS USAGE RELATIONSHIP TO HEATING DEGREE DAYS

Linear regressions to average billing period daily HDD60 were established in the following form:

$$Daily\ therms = A + [B * HDD60]$$

The coefficient *A* can be thought of as the average daily gas usage of appliances not including space conditioning whereas the second term represents space conditioning consumption.

TABLE 19 – DHS DAILY GAS ENERGY REGRESSIONS

	BASELINE	SEALED CRAWL SPACE PHASE	SEALED ATTIC PHASE
A	0.50	0.41	0.45
B	0.24	0.10	0.18
Regression R^2	0.82	0.85	0.75

Using these regression models, the annual energy usage for an average weather year can be estimated. Since the average daily temperatures recorded at local weather station differed significantly from California CZ temperatures, energy usage for the host sites was modeled for an average year using local weather station data over the most recent three years.

Figure 16 and Figure 17 show the baseline and measure phase annual energy usage profiles using this local weather data year. The sealed attic phase saw an increase in energy consumption, perhaps because this constituted additional conditioned space and the ductwork was located in the crawlspace (savings typically present only when space with ductwork is sealed).

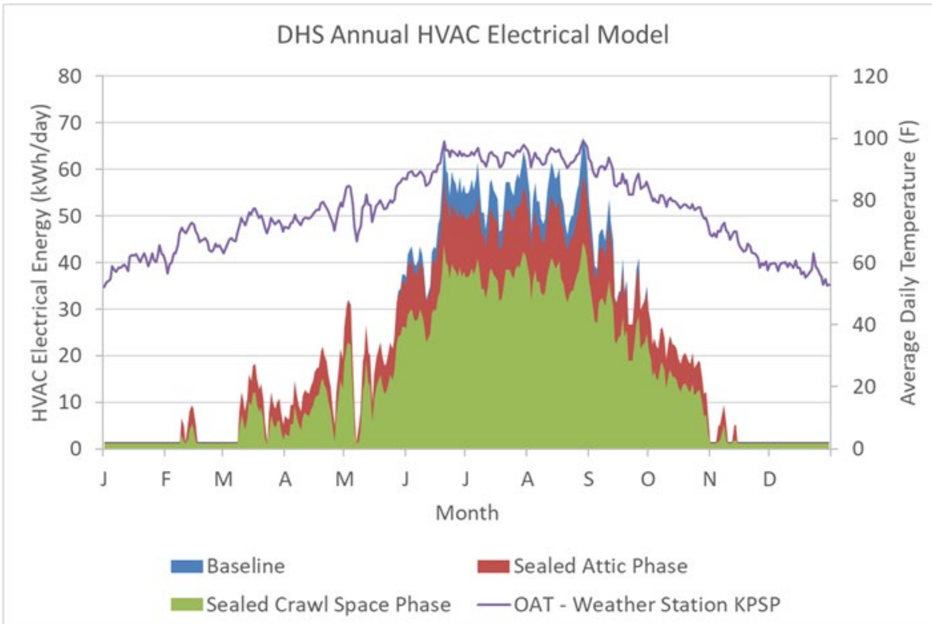

FIGURE 16 - DHS ANNUAL ELECTRIC USAGE PROFILE

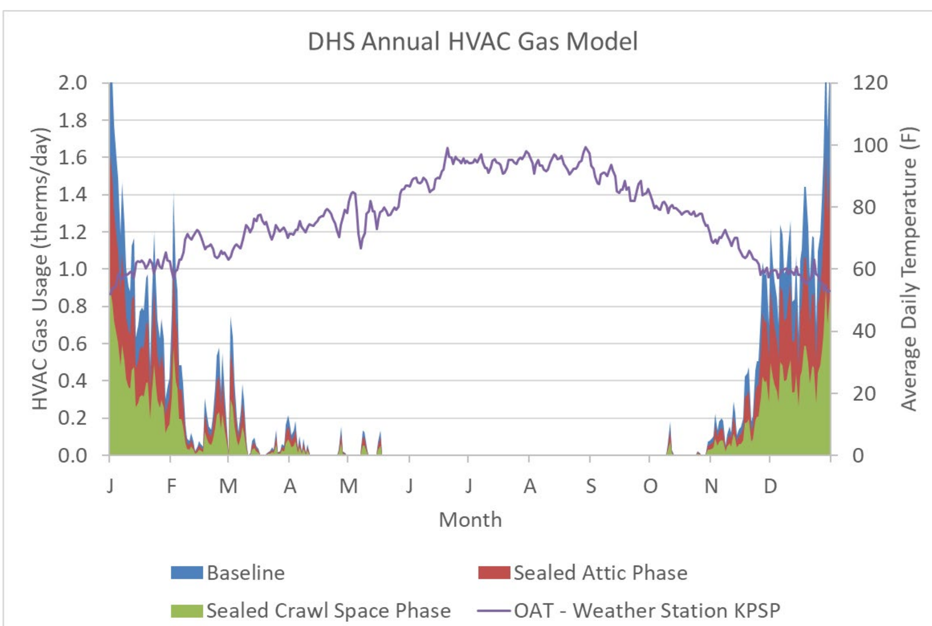

FIGURE 17 - DHS ANNUAL GAS USAGE PROFILE

Similar calculations using CZ data can be performed to extrapolate the building type to standard California CZ weather years. Table 20 lists the estimated energy usage and savings for CZ15 and the local weather data for the models established for the Desert Hot Springs building. The extreme hot weather of the site and occupant behavior may compromise extrapolation to other climate zones. However, for consideration, Appendix A explores CZ extrapolations using the site-specific regressions. Note that savings are pronounced with the crawl space sealing measure because the ductwork was located in the crawl space.

TABLE 20 – ENERGY USAGE AND SAVINGS FOR DHS BUILDING[7]

Local Weather (within CZ15)				
	HVAC Electrical Energy (kWh/yr)	Electrical Energy Savings (kWh/yr)	HVAC Gas Energy (therms/yr)	HVAC Gas Savings (therms)
Baseline	7,695.4		93.9	
Sealed Crawl Space	5,563.1	2,132.3	38.2	55.7
Sealed Attic	7,703.9	-2,140.8	69.3	-31.1
Net		-8.5		24.6
Climate Zone 15				
Baseline	7,960.4		92.7	
Sealed Crawl Space	5,589.4	2,371.1	37.7	55.0
Sealed Attic	7,603.8	-2,014.4	68.4	-30.7
Net		356.7		24.3

The installed measures included a DR-capable thermostat. Since the thermostat was installed during the crawl space retrofits, no baseline DR tests could be conducted. However, several DR tests during the measure phases were conducted to characterize the DR potential and whether the crawl space and attic sealing and conditioning showed any obvious DR benefit such as increased demand reduction or increased thermal inertia to maintain comfortable inside temperatures over the DR event.

[7] Negative values denote energy increases.

During the DR event, thermostat cooling setpoints were increased by 1°F per hour for three hours starting at 2 PM. Demand curves from an adjusted 10-in-10 baseline and the event day showed a demand reduction and an increase in IAT as seen in Figure 18 through Figure 21. Note that the IAT sensor was not located at the thermostat but rather closer to the ceiling to remain hidden. Thus, the IAT values were not necessarily what was felt by the occupants.

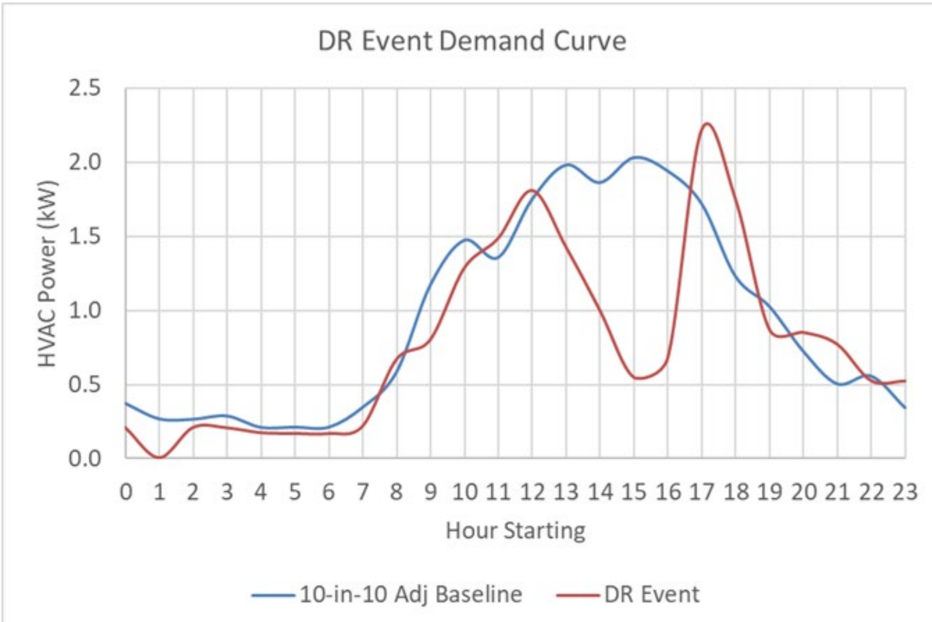

FIGURE 18 - DHS DR TEST 3 DEMAND PROFILE (SEALED CRAWL SPACE PHASE)

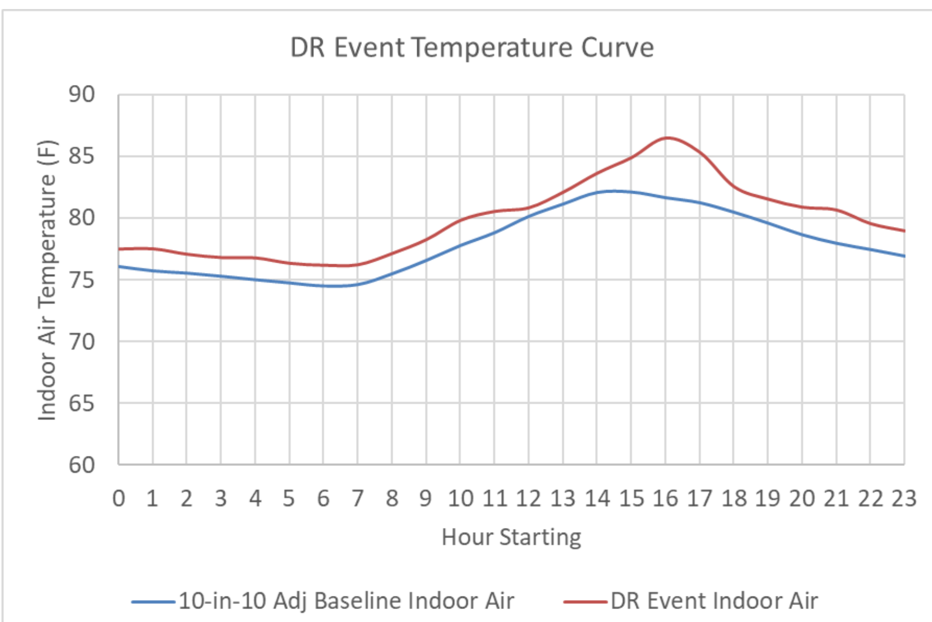

FIGURE 19 - DHS DR TEST 3 TEMPERATURE PROFILE (SEALED CRAWL SPACE PHASE)

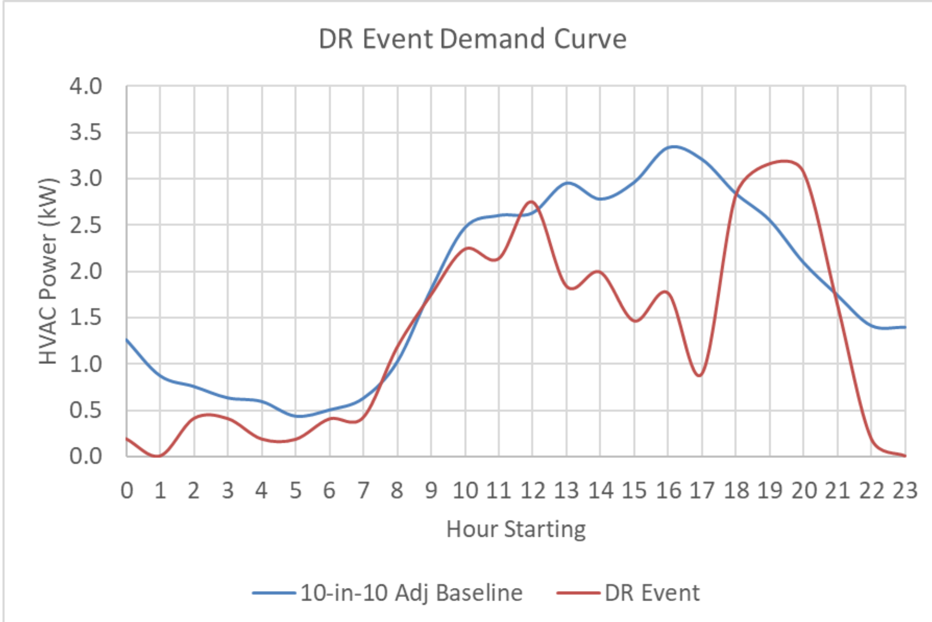

FIGURE 20 - DHS DR TEST 4 DEMAND PROFILE (SEALED ATTIC PHASE)

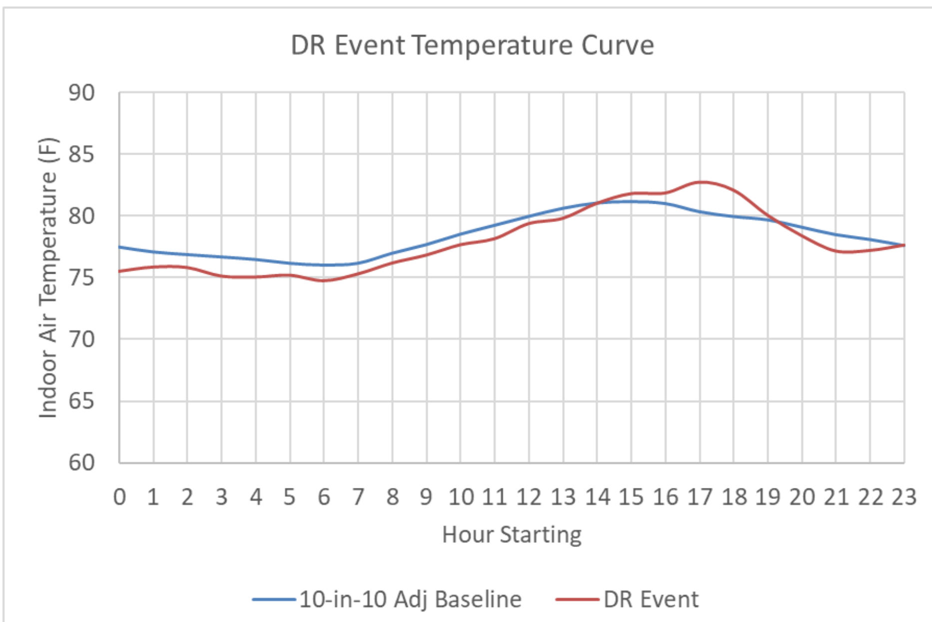

FIGURE 21 - DHS DR TEST 4 TEMPERATURE PROFILE (SEALED ATTIC PHASE)

Table 21 and Table 22 show the hourly-averaged DR test results for the hours between 2-5PM, showing an average demand reduction of about 1.14 kW and 0.98 kW during the peak timeframe for each measure phase, respectively. The temperature increase inside the house was markedly lower during with the addition of conditioned attic space and sealing even though the OAT was higher in the second round of testing. This might suggest that the home was better able to withstand the DR event due to improved envelope tightness and/or increased thermal inertia.

Table 21 - DHS DR Testing - Sealed Crawl Space Phase

	10-in-10 Baseline (Avg kW)	10-in-10 Adjusted Baseline (Avg kW)	Demand Reduction (kW)	Adjusted Demand Reduction (kW)	Event Outdoor Air Temp (F)	Indoor Air Temp Increase (F)
Test 1	1.60	1.92	0.47	0.82	90	8.3
Test 2	1.51	1.81	1.11	1.41	91	5.6
Test 3	1.75	1.95	1.01	1.20	89	4.4
Average	1.62	1.89	0.86	1.14	90	6.1

Table 22 - DHS DR Testing - Sealed Attic Phase

	10-in-10 Baseline (Avg kW)	10-in-10 Adjusted Baseline (Avg kW)	Demand Reduction (kW)	Adjusted Demand Reduction (kW)	Event Outdoor Air Temp (F)	Indoor Air Temp Increase (F)
Test 3	2.52	3.02	0.78	1.28	96	2.4
Test 4	1.63	1.81	0.50	0.68	94	1.1
Average	2.08	2.42	0.64	0.98	95	1.8

Split System with Gas Heat and Attic Ductwork – Fullerton

The Fullerton site is a 1957 single-story building in CZ8 with 1,220 square feet of living space. The house is conditioned by a 3-ton split system with gas heat, centrally located air handler with ductwork in the attic. Blower door testing showed the building had envelope air leakage rates shown in Table 23.

Table 23 - Fullerton Blower Door Tests

	Envelope Leakage at 50 Pa (CFM)	Leakage Reduction at 50 Pa (CFM)	Envelope Leakage (ACH50)	Leakage Reduction (ACH50)
Baseline	2,145		13.2	
Sealed Crawl Space	2,755	-610 (-28%)	16.9	-3.7
Sealed Attic	2,150	605 (22%)	13.2	3.7

The crawl space measure appeared to show a decrease in building air tightness at first. However, later testing showed no overall, net air tightness change suggesting that the measurement was an error, or most of the leakage was through the attic. The crawl space measure included adding a hole in the air handler return pedestal down into the crawl space. This resulted in air circulation between the living space and the crawl space via floor transfer registers.

As seen in Figure 22, IAT had very similar relationships to OAT during the baseline and measure periods. This suggests that occupant preferences and behaviors were consistent across measurement periods.

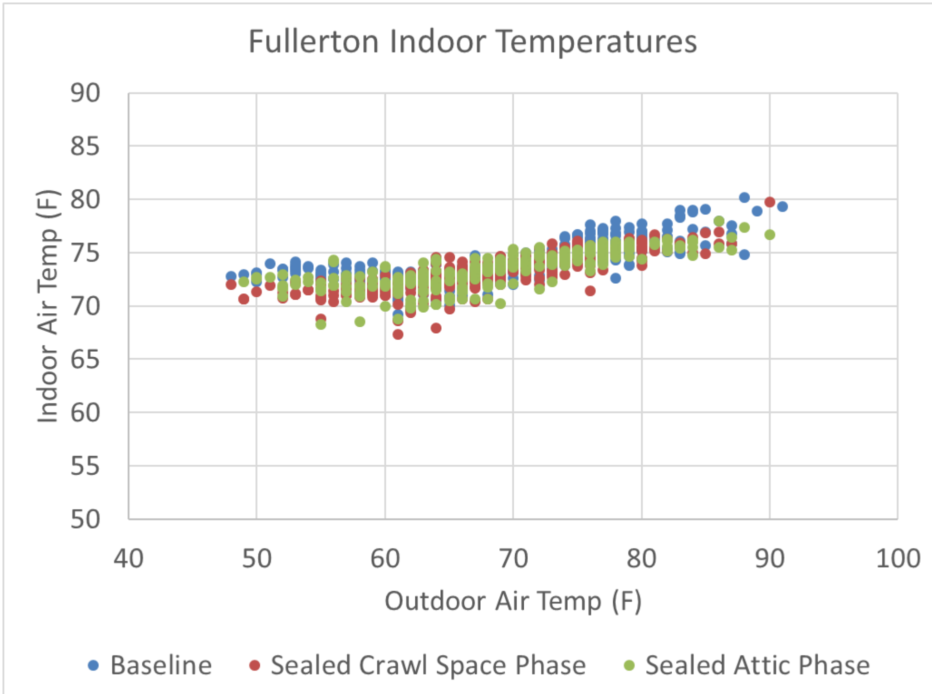

Figure 22 - Fullerton Indoor Air Temperatures

Figure 23 and Figure 24 display this in a different way, showing indoor and outside air conditions on a psychrometric chart. Outside air and inside air conditions were consistent across the test phases.

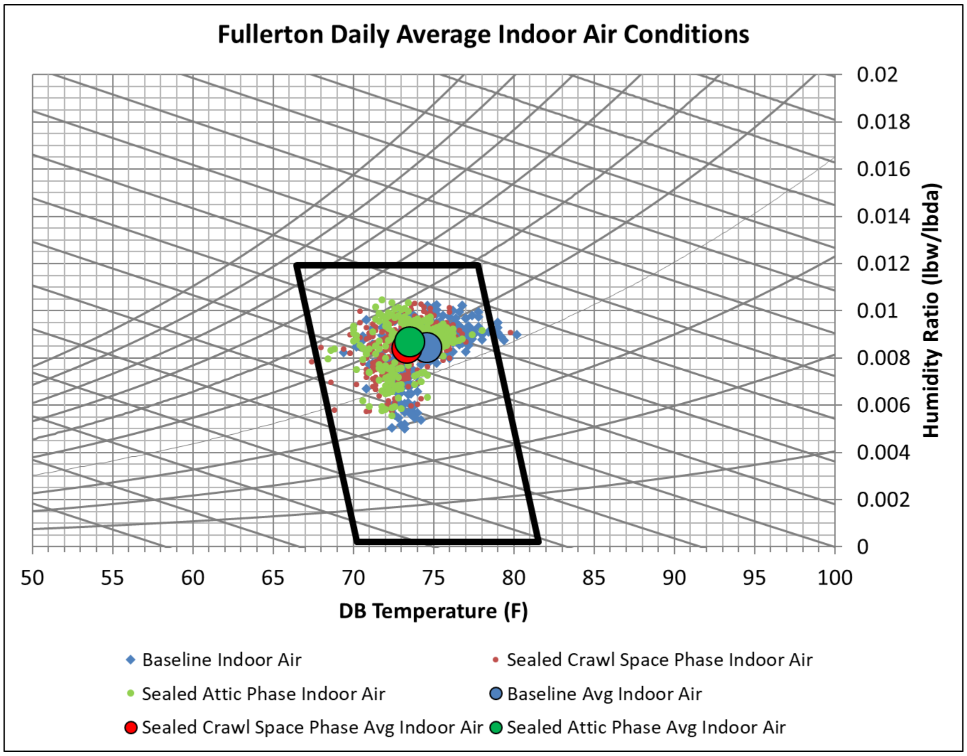

FIGURE 23 - FULLERTON INDOOR AIR CONDITIONS (DAILY AVERAGES)

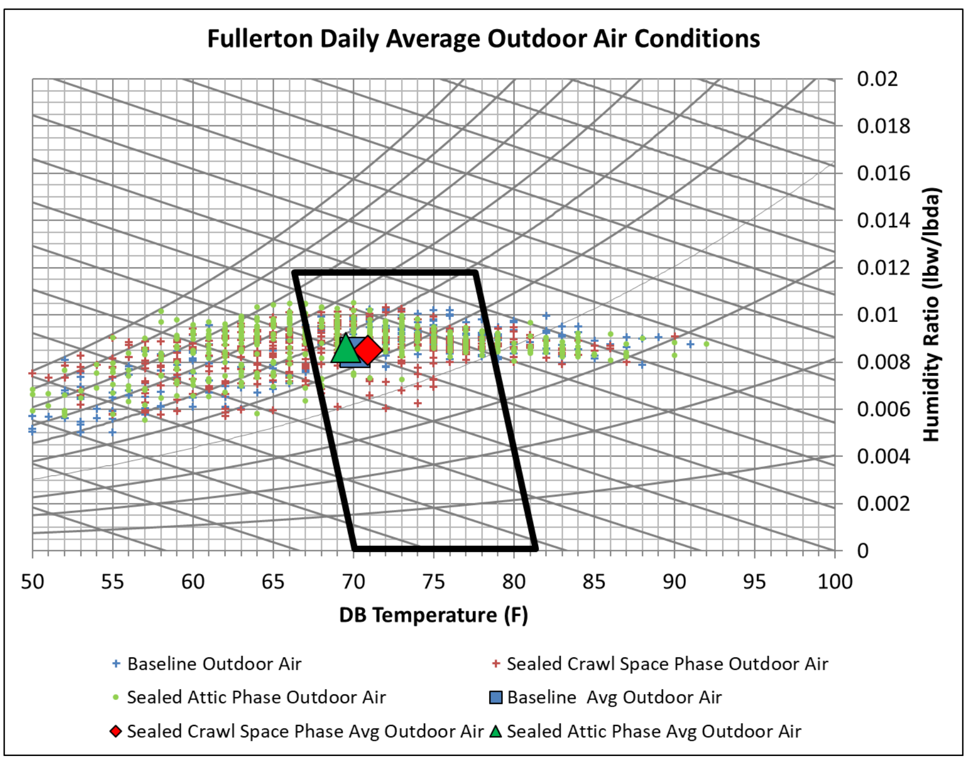

FIGURE 24 - FULLERTON OUTDOOR AIR CONDITIONS (DAILY AVERAGES)

As demonstrated in Figure 25, regression of energy use to OAT can normalize for fair comparison between the periods, assuming consistent behavior. The analysis used a piecewise regression with a change-point at 63F separating heating and cooling conditions.

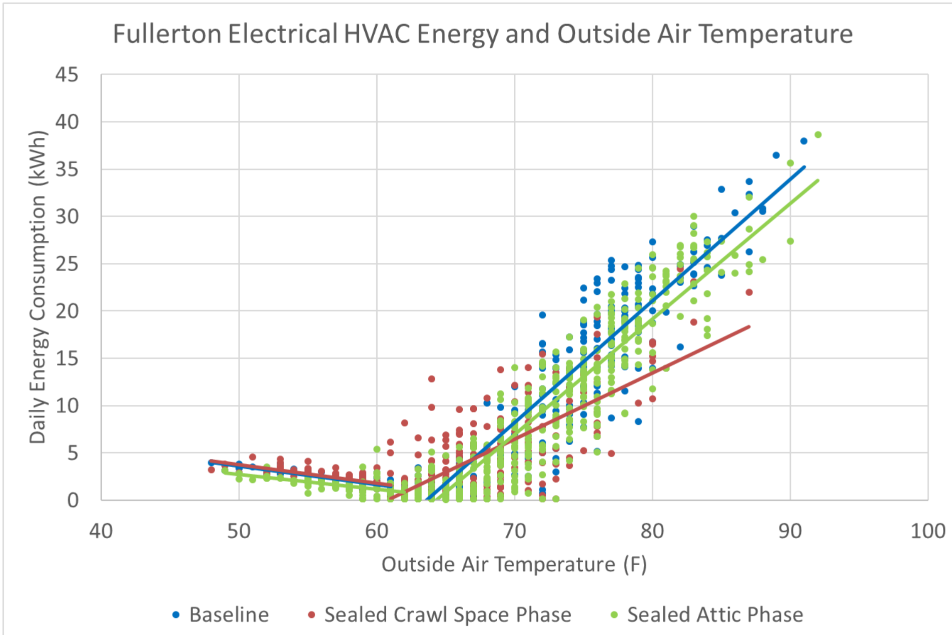

FIGURE 25 - FULLERTON HVAC ELECTRICAL USAGE RELATIONSHIP TO OUTDOOR AIR TEMPERATURE

Linear regression models for electrical energy usage were established based on the data shown in Figure 25:

$$Daily\ kWh = \begin{cases} A + [B * OAT] & for\ all\ OAT < 63 \\ C + [D * OAT] & for\ all\ OAT \geq 63 \end{cases}$$

TABLE 24 - FULLERTON DAILY ELECTRICAL ENERGY REGRESSIONS

	BASELINE	SEALED CRAWL SPACE PHASE	SEALED ATTIC PHASE
A	12.42	13.54	10.74
B	-0.18	-0.19	-0.16
Regression R^2	0.74	0.51	0.32
C	-78.25	-42.47	-78.56
D	1.24	0.70	1.22
Regression R^2	0.80	0.50	0.86

Similarly, linear regressions for gas usage allow for normalized annual energy calculation and savings estimates. Gas data was collected from billing statements, so the measurement intervals were about 30 days and were for the whole building rather than space heating only.

As shown in Figure 26, gas usage has a linear relationship to heating degree days with an optimized base of 60F. Using HDD allows for easy separation of HVAC and non-HVAC gas usage. The y-intercept at zero heating degree days corresponds to non-HVAC gas usage for cooking and domestic water heating. This value can be used to isolate space heating gas usage.

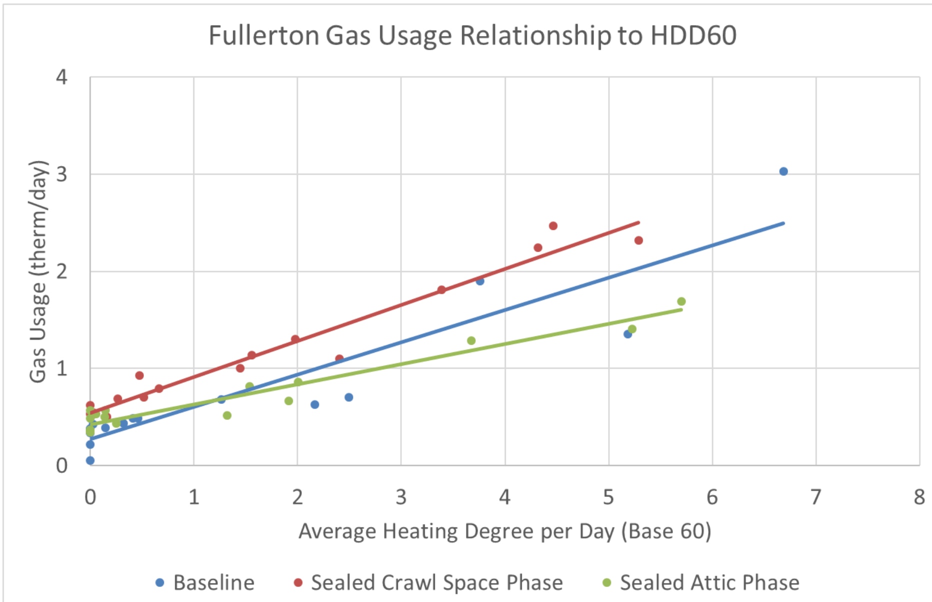

FIGURE 26 - FULLERTON GAS USAGE RELATIONSHIP TO OUTDOOR AIR TEMPERATURE

Linear regressions to average billing period daily HDD60 were established in the following form:

$$Daily\ therms = A + [B * HDD60]$$

The coefficient *A* can be thought of as the average daily gas usage of appliances not including space conditioning whereas the second term represents space conditioning consumption.

TABLE 25 – FULLERTON DAILY GAS ENERGY REGRESSIONS

	BASELINE	SEALED CRAWL SPACE PHASE	SEALED ATTIC PHASE
A	0.26	0.54	0.42
B	0.34	0.37	0.21
Regression R^2	0.86	0.96	0.93

Using these models, the annual energy usage for average host site weather year can be calculated. Since it was observed that the average local weather station daily temperatures differed from California CZ temperatures, energy usage for the host sites was modeled for an average weather year based on the local weather station over the most recent three years.

Figure 27 and Figure 28 show the baseline and measure phase annual energy usage profiles using the average local weather data.

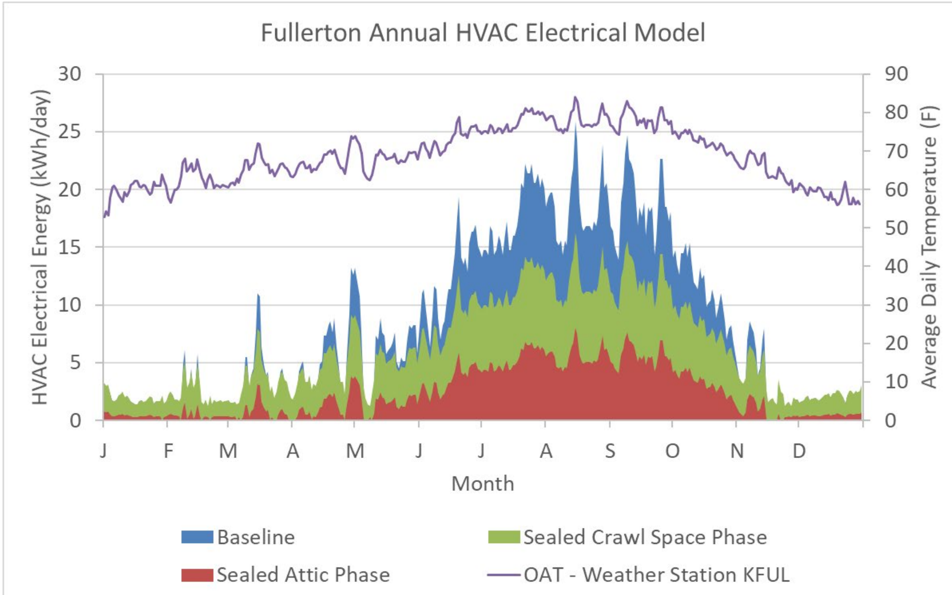

FIGURE 27 - FULLERTON ANNUAL ELECTRICAL USAGE PROFILE

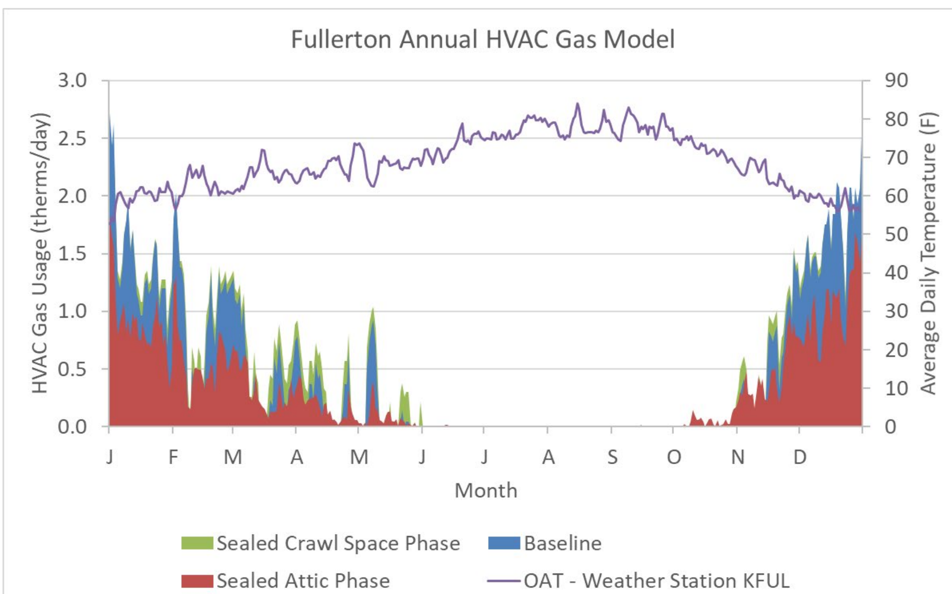

FIGURE 28 - FULLERTON ANNUAL GAS USAGE PROFILE

Table 26 lists the estimated energy usage and savings for CZ8 and the local weather for the Fullerton building type.

TABLE 26 - ENERGY USAGE AND SAVINGS FOR FULLERTON BUILDING TYPE IN STUDIED CLIMATE ZONES[8]

	HVAC Electrical Energy (kWh/yr)	Electrical Energy Savings (kWh/yr)	HVAC Gas Energy (therms/yr)	HVAC Gas Savings (therms)
Local Weather (within CZ8)				
Baseline	3,130.9		180.6	
Sealed Crawl Space	2,302.9	828.0	197.9	-17.4
Sealed Attic	2,640.7	-337.8	109.4	88.5
Net		490.0		71.1
Climate Zone 8				
Baseline	1,704.7		354.3	
Sealed Crawl Space	1,479.5	225.2	388.3	-34.0
Sealed Attic	1,280.7	198.8	214.7	173.6
Net		424.0		139.6

Figure 29 shows the average hourly demand profile for the Fullerton site. It shows that energy savings are distributed almost exclusively during on-peak daytime hours.

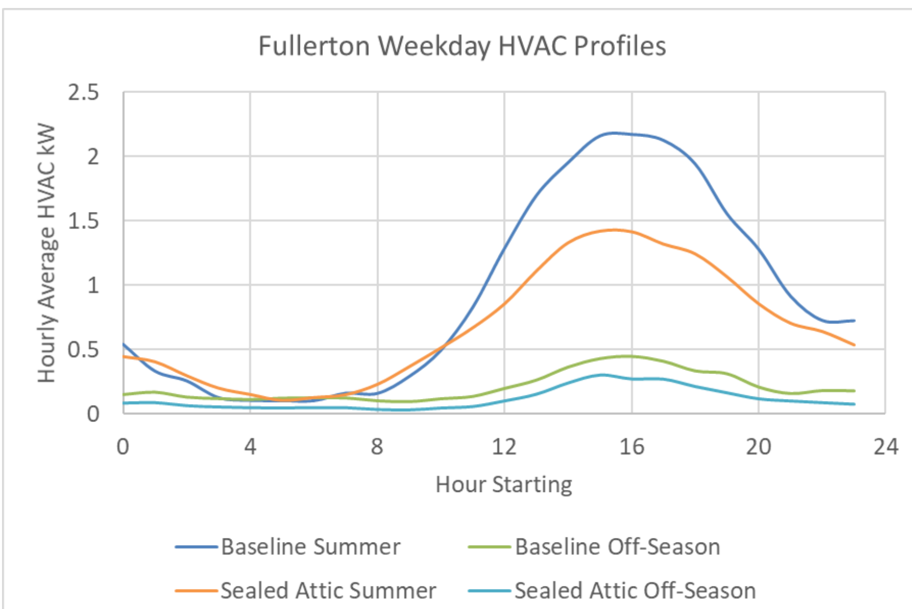

FIGURE 29 - DAILY DEMAND PROFILE FOR FULLERTON SITE

[8] Negative values denote energy increases.

The installed measures included a DR-capable thermostat. Since the thermostat was installed during the crawl space retrofits, no baseline DR tests could be conducted. However, several DR tests during the measure phases were conducted to characterize the DR potential and whether the crawl space and attic sealing and conditioning showed any obvious DR benefit such as increased demand reduction or increased thermal inertia to maintain comfortable inside temperatures over the DR event.

During the DR event, thermostat cooling setpoints were increased by 1°F per hour for three hours starting at 2 PM. Demand curves from an adjusted 10-in-10 baseline and the event day showed a demand reduction and an IAT increase as seen in Figure 30 through Figure 33. The IAT sensor was not located at the thermostat but rather nearer to the ceiling to remain hidden. Thus, the IAT values were not necessarily exactly what was felt by the occupants.

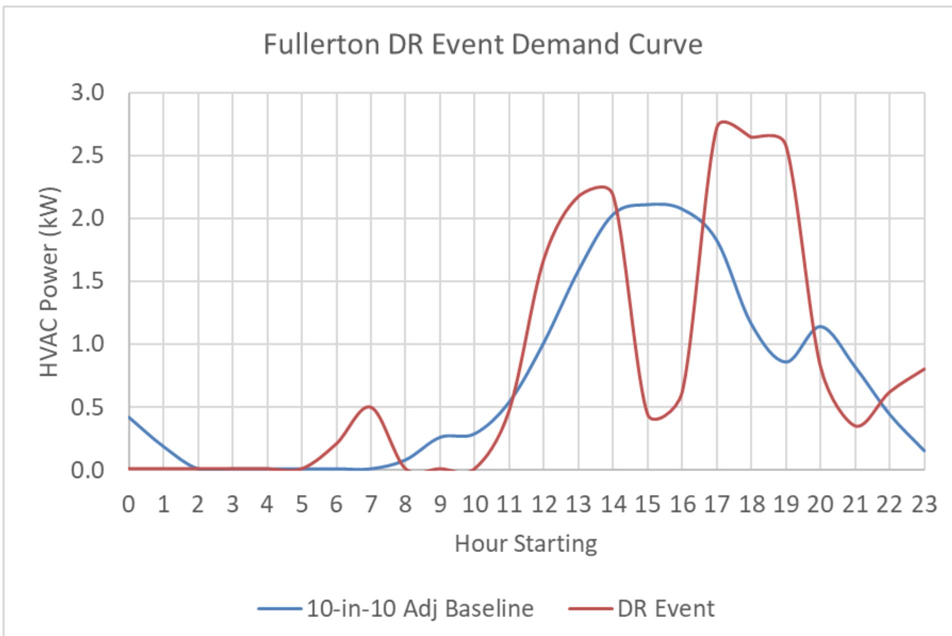

FIGURE 30 - FULLERTON DR TEST 2 DEMAND PROFILE (SEALED CRAWL SPACE PHASE)

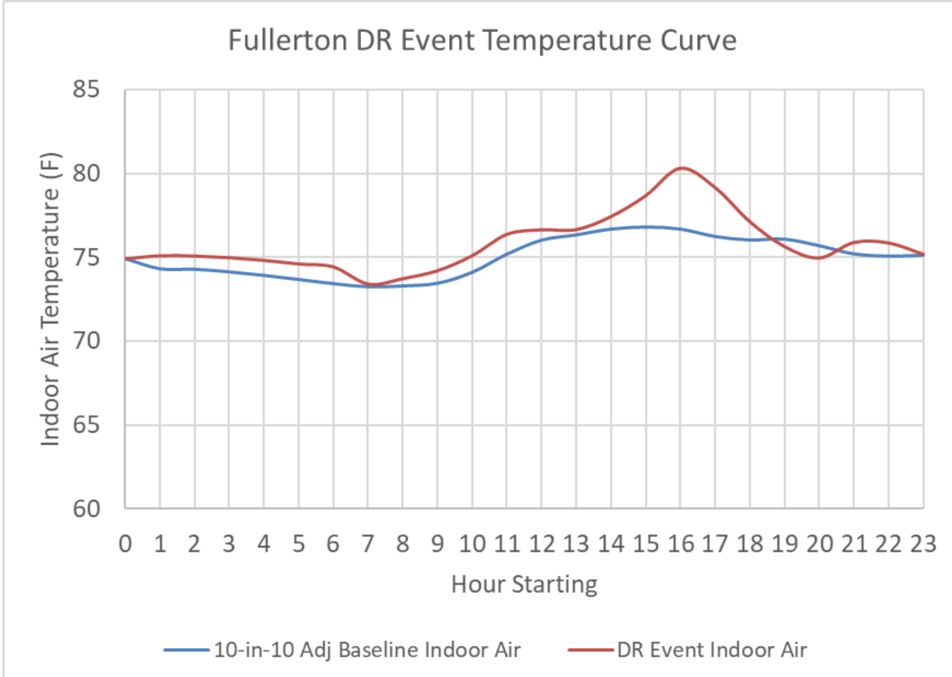

FIGURE 31 - FULLERTON DR TEST 2 TEMPERATURE PROFILE (SEALED CRAWL SPACE PHASE)

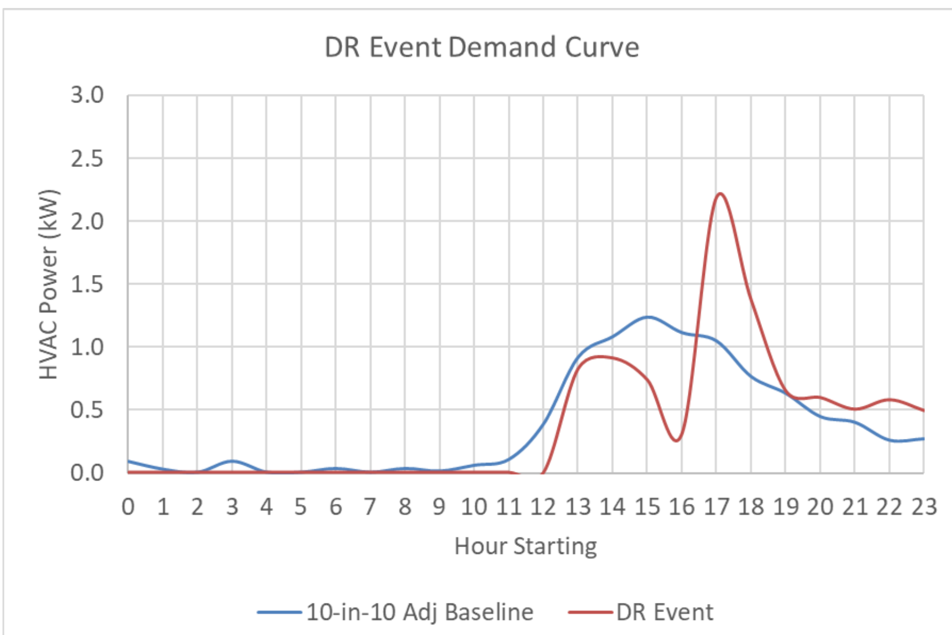

FIGURE 32 - FULLERTON DR TEST 4 DEMAND PROFILE (SEALED ATTIC PHASE)

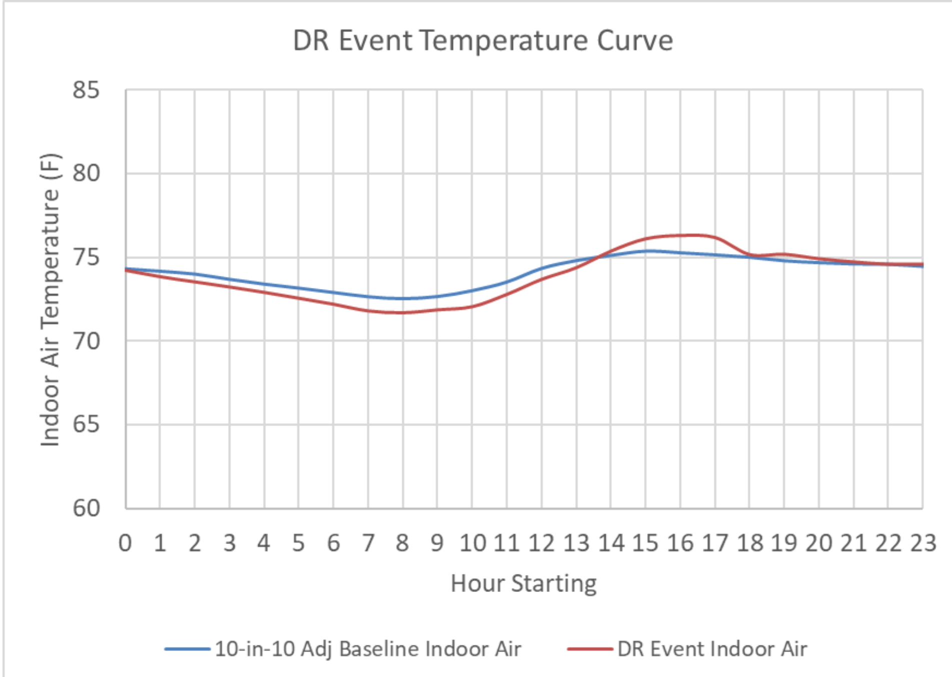

Figure 33 - Fullerton DR Test 4 Temperature Profile (Sealed Attic Phase)

Table 27 and Table 28 show the hourly-averaged DR test results for the hours between 2-5PM, showing an average demand reduction of about 0.95 kW and 0.50 kW during on-peak timeframes for the crawl space and attic phases, respectively. The temperature increase inside the house was markedly lower during with the addition of conditioned attic space and sealing. This might suggest that the home was better able to withstand the DR event due to improved envelope tightness and/or increased thermal inertia.

Table 27 - Fullerton DR Testing - Sealed Crawl Space Phase

	10-in-10 Baseline (Avg kW)	10-in-10 Adjusted Baseline (Avg kW)	Demand Reduction (kW)	Adjusted Demand Reduction (kW)	Event Outdoor Air Temp (F)	Indoor Air Temp Increase (F)
Test 1	1.46	1.75	0.60	0.89	102	3.7
Test 2	1.73	2.08	0.65	1.00	98	3.6
Average	1.62	1.95	0.63	0.95	100	3.7

Table 28 - Fullerton DR Testing - Sealed Attic Phase

	10-in-10 Baseline (Avg kW)	10-in-10 Adjusted Baseline (Avg kW)	Demand Reduction (kW)	Adjusted Demand Reduction (kW)	Event Outdoor Air Temp (F)	Indoor Air Temp Increase (F)
Test 3	0.86	1.03	0.33	0.50	90	2.4
Test 4	0.96	1.15	0.30	0.49	97	1.1
Average	0.91	1.09	0.32	0.50	94	1.8

Supplemented Packaged Heat Pump – Murrieta

The Murrieta site is a 1980 two-story building with 2,440 square feet of living space (1,500 first floor and 940 second floor). The residence is conditioned by a 30,000 Btu/hr heat pump with crawl space ductwork to the first floor, two 5,000 Btu/hr window units on the second floor, and a whole house fan in the attic. There is a second heat pump used to serve the second-story, but it had been out of service for years and had been replaced by the window units. The vented crawl space already had a vapor barrier on the ground before the study began.

Blower door testing showed the building had envelope air leakage rates shown in Table 29. The crawl space sealing measure improved building air tightness by about 8%.

Table 29 - Murrieta Blower Door Tests

	Envelope Leakage at 50 Pa (CFM)	Leakage Reduction at 50 Pa (CFM)	Envelope Leakage (ACH50)	Leakage Reduction (ACH50)
Baseline	5,025		13.7	
Sealed Crawl Space	4,615	410 (8%)	12.6	1.1

As seen in Figure 34 and Figure 35, the overall average OAT and IAT for the measurement period shifted slightly warmer. However, this is likely to due to a measurement gap during the baseline summer months rather than an effect of the measure.

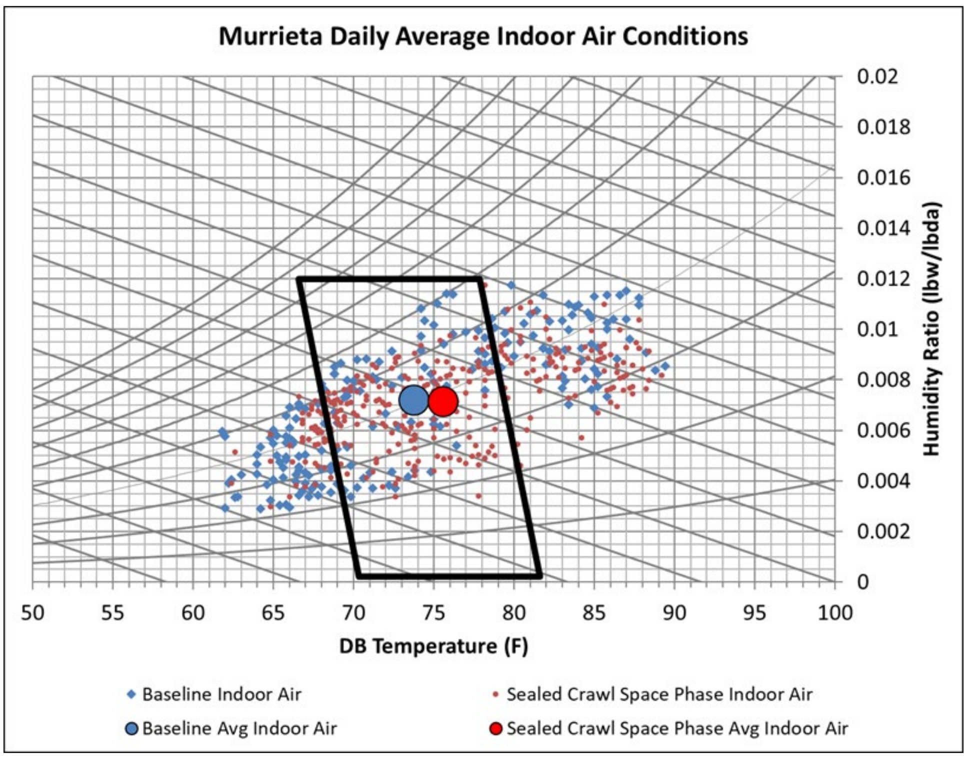

Figure 34 - Murrieta Indoor Air Temperatures (Daily Averages)

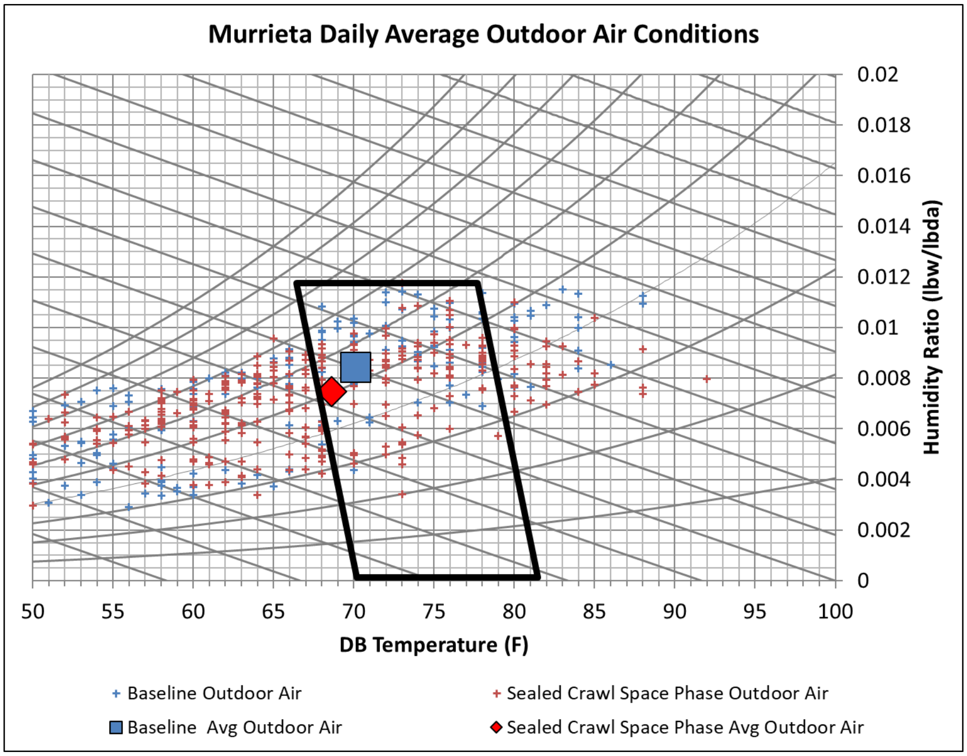

FIGURE 35 - MURRIETA OUTDOOR AIR TEMPERATURES (DAILY AVERAGES)

For the Murrieta site, electrical energy usage was found to have a significant relationship to OAT, OAT^2, and IAT. Other regressions options were tested (piecewise, linear, etc.) but all showed similar results. However, the post-measure relationship to OAT appears to be largely unchanged.

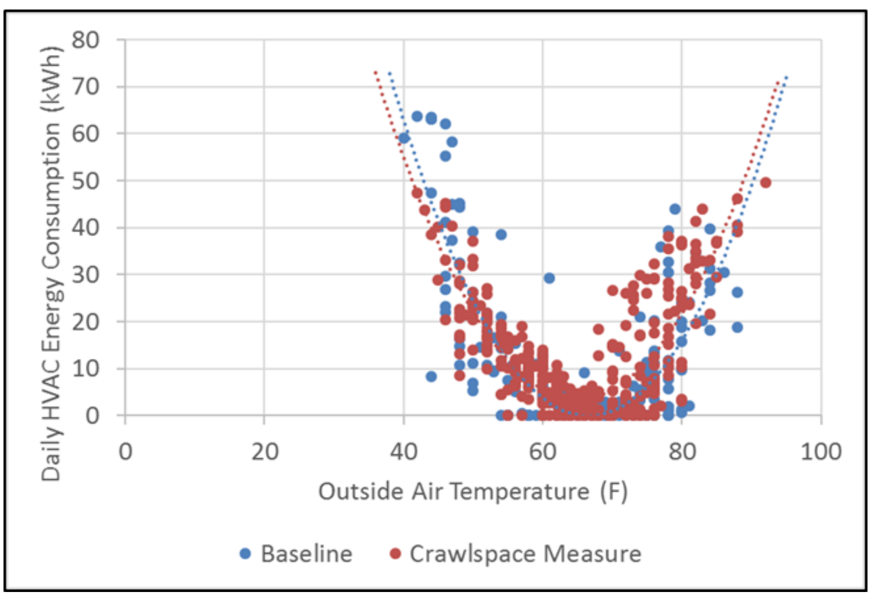

FIGURE 36 - MURRIETA HVAC ENERGY RELATIONSHIP TO OUTDOOR AIR TEMPERATURE

Due to the uncertainty in normalized savings and stark similarity between the baseline and post-measure case regressions, there was no clear evidence that the measure significantly affected energy consumption at this site. The authors conclude that there was little-to-no effect on energy usage at this site, similar to what has been found occasionally by other studies.

Although the Murrieta site saw no obvious energy savings, the regression analysis was still performed. Regressions consistently showed a small unexplained shift upwards in the post period, even in comfortable weather conditions. It should be noted that many variables affecting the energy consumption were not controlled in this study like number of occupants, setpoints, etc.

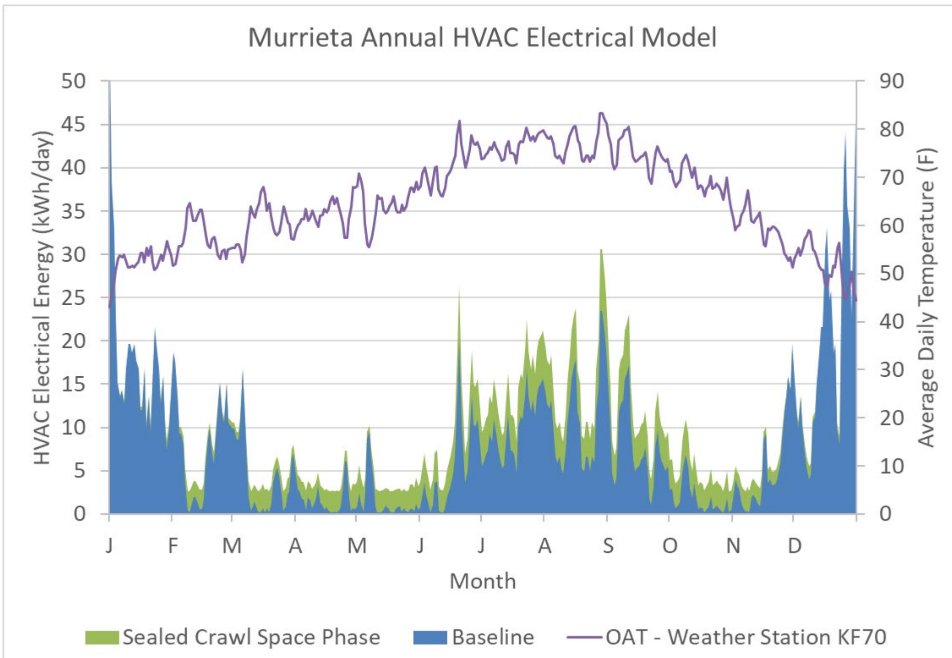

FIGURE 37 - MURRIETA ANNUAL ELECTRIC USAGE PROFILE

In all cases, the all-electric model for the Murrieta site showed energy increases for all tested climate zones. It is not clear why this is the case, especially since blower door testing showed a decrease in building leakage. However, the Murrieta site data was confounded by a few factors:

- Pre-existing crawl space vapor barrier during baseline period.
- Measurement data gap during the baseline summer months.
- Changing occupant behavior patterns appear to have resulted in a shift upwards in energy consumption during the post-measure period.
- Best-fit regressions were shifted up by a small daily constant in the post-period resulting in increased energy usage roughly equal to this small modeling discrepancy.

Additionally, the Murrieta site did not yield any usable DR tests. Occupant preferences and thermostat setpoints leading up to the DR events, or on during event days, showed too infrequent HVAC usage to establish a baseline or event day profile for each test that was performed. Existing setpoints were frequently found to be 82-95 °F during DR event tests.

WINDOW UNITS – POMONA

The Pomona site is a 1920 single-story building with 1,160-square feet of living space and two window units in CZ9. Blower door testing showed the building had envelope air leakage rates shown in Table 30. The crawl space sealing did not have much effect on building tightness, suggesting that other parts of the building were responsible for the high leakage rate. Indeed, the attic had very large outside air vents and the attic sealing reduced building leakage at 50 Pa by 10%.

TABLE 30 - POMONA BLOWER DOOR TESTS

	ENVELOPE LEAKAGE AT 50 PA (CFM)	LEAKAGE REDUCTION AT 50 PA (CFM)	ENVELOPE LEAKAGE (ACH50)	LEAKAGE REDUCTION (ACH50)
Baseline	5,810		37.6	
Sealed Crawl Space	5,735	73 (1%)	37.1	0.5
Sealed Attic	5,195	540 (10%)	33.6	3.5

As seen in Figure 38, IAT followed the same trend during the baseline and measure periods. Based on the similar IAT trends across measurement periods and the insignificant relationship between energy consumption and IAT, no normalization of IAT and occupant behavior in the energy modeling was necessary.

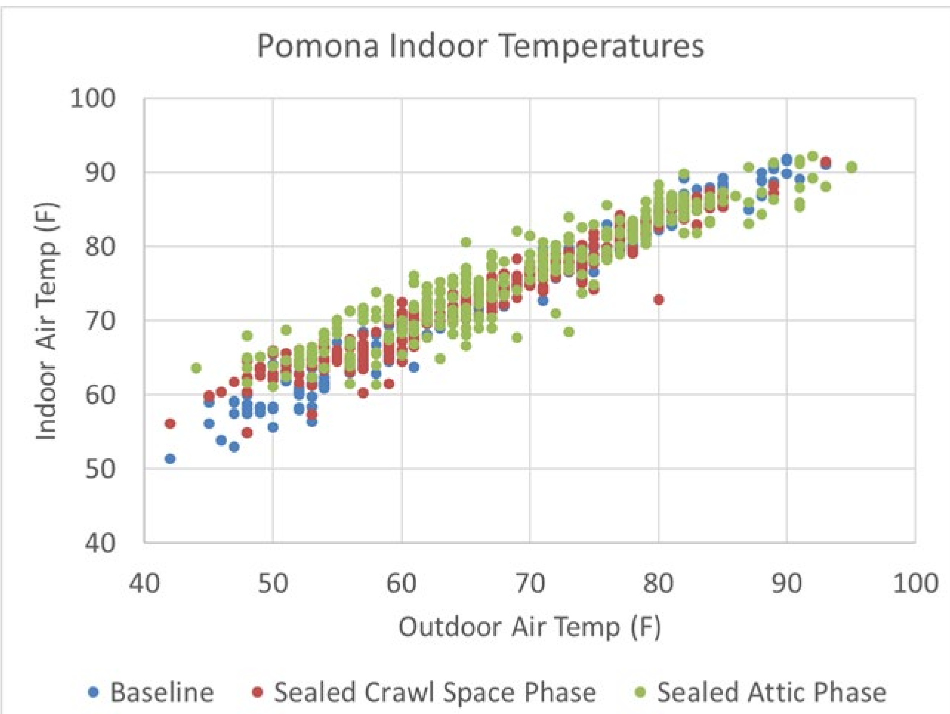

FIGURE 38 - POMONA INDOOR AIR TEMPERATURES

In Figure 40, the change in overall average OAT is driven by a data collection gap during the baseline summer months.

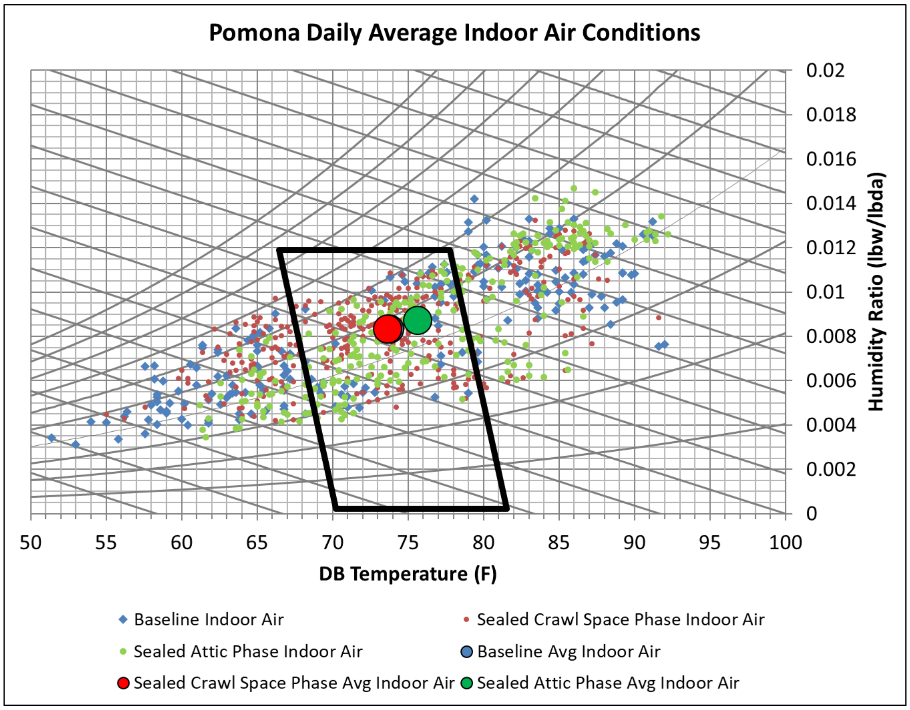

FIGURE 39 - POMONA INDOOR AIR CONDITIONS (DAILY AVERAGES)

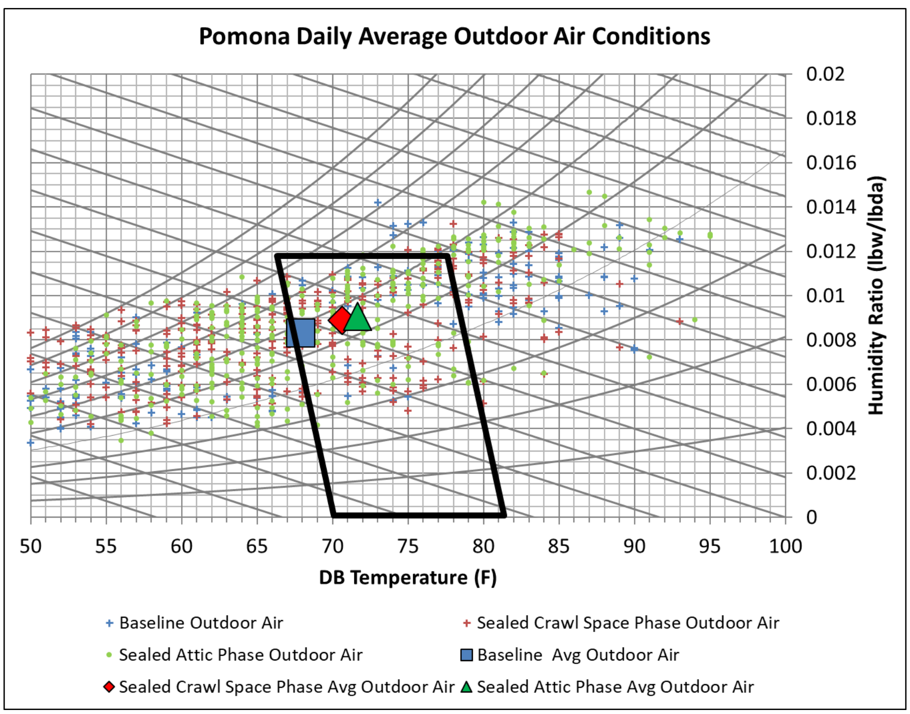

FIGURE 40 - POMONA OUTDOOR AIR CONDITIONS (DAILY AVERAGES)

For the Pomona site, electrical energy use was found to have the most robust relationship to CDD with a base of 85. This variable was found to be more robust than OAT and can account for occupant comfort preferences more readily than average daily OAT. This is an unusually high base temperature, but the window unit usage patterns confirm that the occupants rarely used cooling and only at high temperatures.

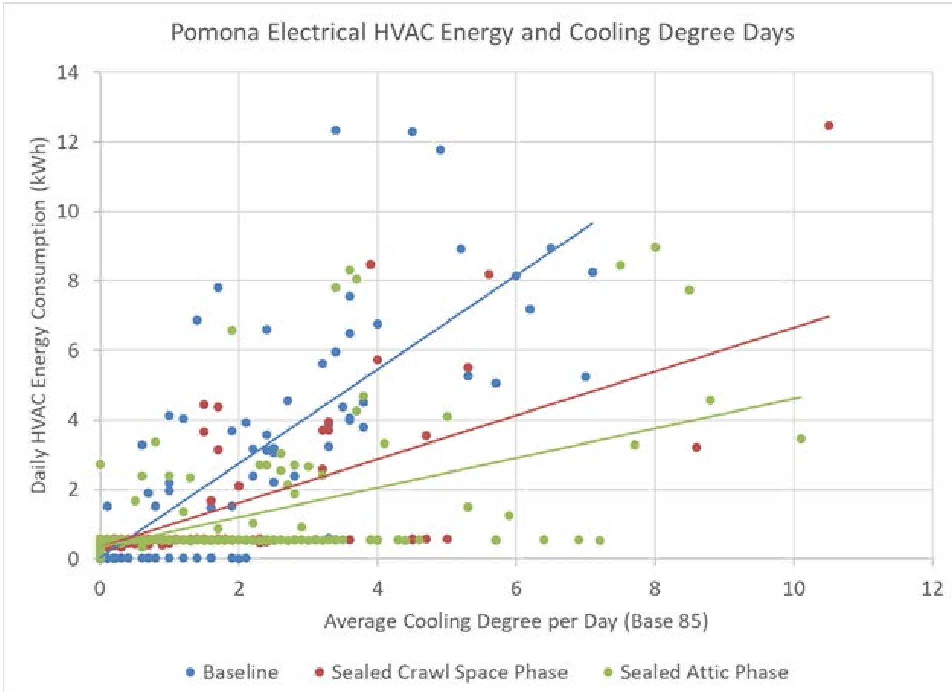

FIGURE 41 - POMONA HVAC ENERGY RELATIONSHIP TO COOLING DEGREE DAYS

Linear regression models for electrical energy usage were established based on the data shown in Figure 41 to estimate annual usage. A ducted fan was installed to transfer air between the crawl space and living space to generate circulation through the two spaces. Note that the increased y-axis intercept for the crawl space and attic measure periods is roughly equivalent to the daily energy consumption of the transfer fan which often ran even when cooling was not necessary.

Linear regression models for electrical energy usage were established based on the data shown in Figure 41:

$$Daily\ kWh = A + [B * CDD85]$$

TABLE 31 - POMONA DAILY ELECTRICAL ENERGY REGRESSIONS

	BASELINE	SEALED CRAWL SPACE PHASE	SEALED ATTIC PHASE
A	0.028	0.34	0.34
B	1.35	0.63	0.43
Regression R^2	0.72	0.49	0.34

Figure 42 shows the baseline and measure phase annual energy use profiles using the average local weather data.

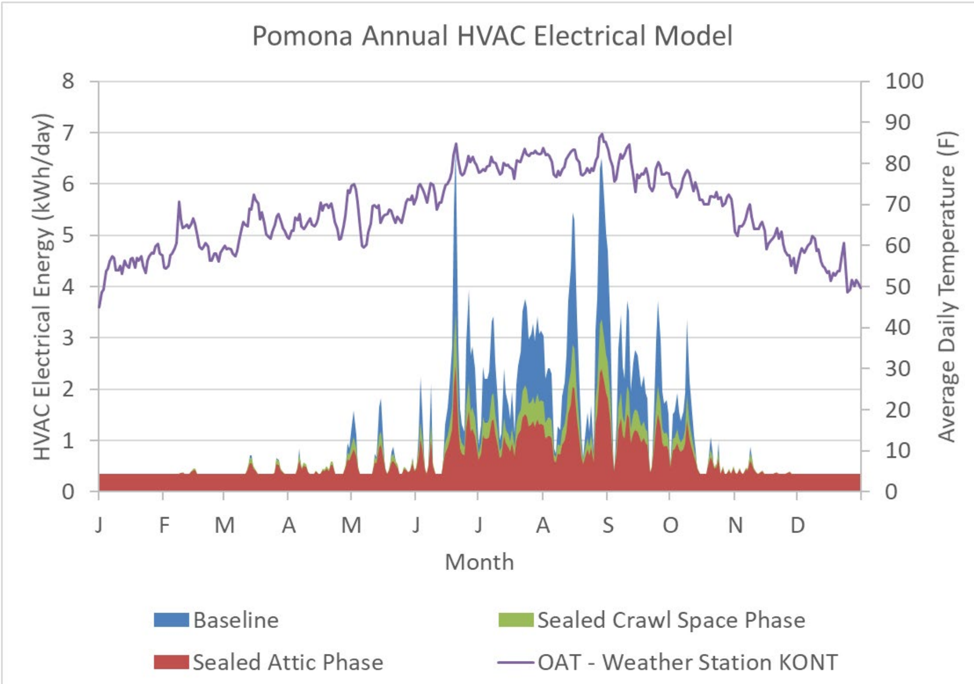

FIGURE 42 - POMONA ANNUAL ELECTRIC USAGE PROFILE

Table 32 lists the estimated energy usage and savings for CZ9 and the local weather data for the models established for the Pomona building type.

TABLE 32 - ENERGY USAGE AND SAVINGS FOR POMONA BUILDING TYPE IN STUDIED CLIMATE ZONES[9]

Local Weather (within CZ9)		
	HVAC Electrical Energy (kWh/yr)	Electrical Energy Savings (kWh/yr)
Baseline	344.4	
Sealed Crawl Space	280.3	64.1
Sealed Attic	231.0	49.3
Net		113.4
Climate Zone 9		
Baseline	144.9	
Sealed Crawl Space	187.0	-42.4
Sealed Attic	167.9	19.1
Net		-23.3

[9] Negative values denote energy increases.

DISCUSSION AND CONCLUSIONS

The field assessment of conditioned, sealed crawl spaces and attics under differing conditions produced a variety of results. Four sites were monitored for three seasons under existing baseline conditions and one year after each crawl space and attic sealing retrofit. Normalized energy savings were calculated for each site and extrapolated to the other participating CZs for comparison. Indoor air quality was observed, and DR tests were performed during the measure periods. The market size, potential savings, and barriers were studied. These measures are particularly useful for homes with ductwork in the sealed space, high envelope leakage, high duct leakage, excessive crawl space or attic venting, homes with little insulation, and homes with high HVAC energy usage.

The Desert Hot Springs building in CZ15 with packaged DX cooling, gas heat, and ductwork in the crawl space saw a net savings of 0% electricity and 26% gas. However, the crawl space measure alone yielded savings of 28% electricity and 59% gas. This is likely because the ductwork was located in the crawl space and thus savings largely came from mitigating duct leakage effects. The attic measure somewhat reversed these savings, perhaps due to additional conditioned space loads.

The Fullerton building in CZ8 with split DX cooling, gas heat, and ductwork in the attic saw a net savings of 16% electricity and 39% gas. However, the energy impacts at this site differed between the crawl space and attic phases. Electrical energy usage was reduced after crawl space sealing by 26% but increased during the attic phase. To condition the crawl space at this site, the closet air handler’s return was dropped into the crawl space instead of drawing from the living space. Thus, during the crawl space phase, drawing cooler air from the crawl space may have caused the electrical energy savings. However, during the attic phase, the added conditioned space in the attic may have increased the cooling energy usage by adding unnecessary load without cooling benefits. On the other hand, gas usage increased during the crawl space phase but had 45% savings after attic sealing. Converse to the electrical usage effects, this may be due to increased crawl space heating loads in the first phase and smaller duct leakage effects in the attic in the second phase.

The Pomona building in CZ9 with window units used very little HVAC energy to begin with but saw building tightness improvements, especially after attic sealing due to a very leaky baseline attic. The Pomona site saw equal electrical savings during the crawl space and attic phases for a net 32% savings, perhaps due to the lack of ductwork influencing the measures.

In all cases, the electrical savings effects were amplified in hotter climate zones (e.g. CZ15) while gas savings were amplified in colder climate zones (e.g. CZ8).

Carbon monoxide and radon levels in the homes were not significantly affected and the levels stayed roughly the same after retrofits and within safety limit recommendations. Humidity levels in the crawl spaces and attics were reduced for all four sites with each successive measure. During the baseline, three of the houses saw RH levels exceed the recommended limit of 70% with regularity. After the sealing measures, crawl space and attic RH levels were reduced below the recommended limit under all conditions. This confirms previous conclusions that venting is not strictly necessary for moisture control and that sealing with a vapor barrier may work better in most cases. As stated elsewhere, care must be taken at the envelope to ensure proper ventilation by leaving gaps between the sealing layers and roof deck or crawl space walls.

Comfort conditions were generally unaffected or slightly improved at all sites. The daily average IAT and RH levels were all within the ASHRAE comfort zone limits after the measure implementation. It is not possible to determine whether this was a result of the sealing measures or the new thermostats that were installed. It is likely both had a positive effect on comfort levels.

Successful DR simulations were conducted at two of the four sites. These tests were conducted by remotely adjusting the thermostat setpoint by one degree Fahrenheit per hour over three on-peak summer hours. The two sites showed average, baseline adjusted DR reductions of 0.50 to 1.14 kW (40-60%), similar to other residential DR testing in other studies (Southern California Edison, 2009).

Unfortunately, the DR-enabled thermostats were not installed in the baseline so there could not be a comparison of the DR potential with and without the measures. The hypothesis was that the added thermal mass and "stored cooling" in the crawl space would allow for more comfortable temperatures, and reduced compressor cycling during a DR event. It was observed, however, that IAT increased rapidly during the crawl space phase DR tests and occupants had to be reminded not to adjust the thermostat during the test or overridden. This suggests that the increase in IAT was excessive for their comfort even after crawl space sealing. The data showed that the additional attic sealing appeared to have mitigated this issue. The increased building tightness and thermal inertia overall eased the effects of residential DR measures on indoor air temperatures and comfort conditions. In this manner, sealing may increase the viability of residential DR HVAC measures associated with compressor cycling or setpoint adjustments.

The market size for the crawl space sealing measure for existing homes is roughly 441,600 SFR homes in SCE service territory and 1,387,700 across California. These are single family homes with vented, unconditioned crawl spaces. The market size for the attic sealing measure is roughly 2,650,100 homes in SCE territory and 8,030,600 homes in California. Of these, about 66% and 56% have central air in SCE service territory and California, respectively. If the Fullerton and Desert Hot Springs sites are considered typical of these SFR buildings and if the measures are properly selected, the energy savings potential is on the order of 400 and 1,100 GWh/year for SCE service territory and California existing homes, respectively. Homes with window units comprise an additional market, but savings may only be significant in CZ15 where most SFRs will have central air.

Those with ductwork in the crawl space or attic should be the primary target of outreach due to the highest energy savings opportunity. The market share of new construction homes with crawl spaces does appear to be decreasing over the last several years but does not necessarily imply a permanent trend.

The average cost of the crawl space measure for the sites was about $8.70 per square foot of crawl space area while the attic cost was $6.70. Simple payback for the measures at the sites would be over 30 years based on the data collected and the project costs. However, there are several factors that make this measure attractive despite this long payback from energy savings alone:

- Non-energy benefits include reduced risk of dry rot, mold, water, and pests that can add to cost savings and increased building lifespan.
- Non-energy benefits include improved IAQ and health effects such as lessened risk of asthma and potentially less radon exposure.
- Costs would likely decrease as service providers became familiar with the measure and with increased competition.

- Time-dependent valuation (TDV) energy and cost savings (not directly seen by the customer) would be very different from the billing savings and would add more societal benefit than the calculated cost savings suggest. The electrical energy savings are concentrated during the cooling season with almost all occurring during daytime hours.
- Payback would be much better for new construction buildings or if work in the crawl space is already being performed.
- The additional cool air and increased thermal inertia likely marginally increase the DR effectiveness, but the tests could not quantify this effect with specificity due to small sample sizes.

Since this is a set of construction retrofit measures, there are significant market barriers to adoption. Customer cost is high and potential benefits are not well known. It is unlikely that homeowners would consider sealing and conditioning their crawl spaces when there are competing priorities associated with other home repair and maintenance needs. This resistance could potentially be mitigated through market outreach of the benefits and appropriateness of the application, incentives, or leveraging opportunities when homeowners already need to do projects such as rodent-proofing, insulation, moisture or radon mitigation, leak repair, or ducting repair.

None of the commonly used building modeling software (such as CBECC-Res or eQuest) allows for modeling of sealed, conditioned crawl spaces without customizing geometries. This is a market barrier that would have to be addressed, particularly in the new construction market. The other primary barrier, especially in retrofit cases, is limited contractor awareness, familiarity, and expertise (Dastur, 2009). It is difficult to find contractors who are qualified and interested in doing this type of retrofit. Construction guides for conditioned crawl spaces and attics have been published but market adoption and contractor awareness remain low (Advanced Energy, 2005). The measures could be promoted through outreach to contractors and new home builders through workshops and other promotional and training programs. Builders and contractors still sometimes avoid the measure based on the misunderstanding that it is not allowed under code since vented crawl spaces used to be required (Lstiburek, 2004). Ideally, studies such as this one, outreach, promotion, support, and construction guidelines can help spur market adoption.

RECOMMENDATIONS

Based on the promising nature of the measure and variety of benefits, consideration for program support is advised. Recommended courses of action for furthering market adoption include the following:

- Gather construction and industry professionals for a workshop to identify opportunities for cost reduction and standardization.
- Perform a comprehensive building modeling study and a sensitivity analysis of building conditions, measure design, and climate zones to determine optimal building and sub-sector targets for existing or new construction programs.
- Study code change implications (crawl space measure only) since new building costs are lower and TDV savings would likely provide improved cost-benefit.
- Any subsequent studies should focus on controlling conditions as much as possible. For instance, any future study should install programmable thermostats with appropriate settings before the baseline. This will allow for baseline DR testing and help to avoid changes to occupant behavior due to improved setpoint control. Additionally, occupants should be screened for their HVAC use and setpoint preferences prior to enrollment to avoid unusual cases such as the Murrieta and Pomona sites. Several planned side-by-side, unoccupied, controlled sites for this study had been planned but could not be included. This type of test site could help maintain control conditions.
- The highest savings building type is older homes with ductwork in vented crawl spaces or attics, especially if the return and supply are co-located in the same space (attic or crawl space). The measure impacts are complicated when return and supply are located in both the attic and crawl space. Any targeted programs could focus on buildings with attic-only or crawl space-only ductwork first.
- Develop custom modeling of buildings with conditioned crawl spaces to inform changes to compliance and whole building software such as CBECC-Res.
- Leverage previous CASE work to model sealed, conditioned attics in existing homes.
- Explore options for optimizing crawl space airflow during heating and cooling seasons. Energy penalties may exist during heating season that could potentially be mitigated by control strategies.
- Potential program support includes code changes, new construction energy budgeting of conditioned crawl space savings, contractor outreach and training, and incentives for retrofits potentially packaged with other measures for improving overall cost-effectiveness.

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APPENDIX A – CZ EXTRAPOLATIONS

Although each building had site-specific uncontrolled conditions, the regressions were applied to each studied climate zone for consideration and comparison among the four case studies. For instance, as seen in Table 33, the DHS model shows much lower energy usage in the other CZs than observed in-situ. This could be due to the unique conditions at DHS that may hinder extrapolation to other CZs. However, the estimated HVAC energy use for the extrapolated climate zones (CZ8, 9, and 10) are within expected HVAC end-use consumption (KEMA, 2010).

TABLE 33 – ENERGY USAGE AND SAVINGS FOR DHS BUILDING TYPE IN STUDIED CLIMATE ZONES[10]

	HVAC Electrical Energy (kWh/yr)	Electrical Energy Savings (kWh/yr)	HVAC Gas Energy (therms/yr)	HVAC Gas Savings (therms)
Local Weather (within CZ15)				
Baseline	7,695.4		93.9	
Sealed Crawl Space	5,563.1	2,132.3	38.2	55.7
Sealed Attic	7,703.9	-2,140.8	69.3	-31.1
Net		-8.5		24.6
Climate Zone 8				
Baseline	763.9		251.3	
Sealed Crawl Space	738.3	25.7	102.2	149.0
Sealed Attic	1,090.5	-352.2	185.4	-83.1
Net		-326.5		65.9
Climate Zone 9				
Baseline	972.3		138.5	
Sealed Crawl Space	958.8	13.4	56.3	82.1
Sealed Attic	1,457.8	-499.0	102.2	-45.8
Net		-485.6		36.3
Climate Zone 10				
Baseline	1,548.9		221.1	
Sealed Crawl Space	1,349.5	199.4	90.0	131.1
Sealed Attic	1,984.0	-634.6	163.1	-73.2
Net		-435.1		58.0
Climate Zone 15				
Baseline	7,960.4		92.7	
Sealed Crawl Space	5,589.4	2,371.1	37.7	55.0
Sealed Attic	7,603.8	-2,014.4	68.4	-30.7
Net		356.7		24.3

[10] Negative values denote energy increases.

Table 34 lists similar regression extrapolations for the Fullerton site.

TABLE 34 - ENERGY USAGE AND SAVINGS FOR FULLERTON BUILDING TYPE IN STUDIED CLIMATE ZONES[11]

	HVAC Electrical Energy (kWh/yr)	Electrical Energy Savings (kWh/yr)	HVAC Gas Energy (therms/yr)	HVAC Gas Savings (therms)
Local Weather (within CZ8)				
Baseline	3,130.9		180.6	
Sealed Crawl Space	2,302.9	828.0	197.9	-17.4
Sealed Attic	2,640.7	-337.8	109.4	88.5
Net		490.0		71.1
Climate Zone 8				
Baseline	1,704.7		354.3	
Sealed Crawl Space	1,479.5	225.2	388.3	-34.0
Sealed Attic	1,280.7	198.8	214.7	173.6
Net		424.0		139.6
Climate Zone 9				
Baseline	1,973.8		195.2	
Sealed Crawl Space	1,613.0	360.8	214.0	-18.8
Sealed Attic	1,576.8	36.2	118.2	95.7
Net		397.0		76.9
Climate Zone 10				
Baseline	2,434.4		311.7	
Sealed Crawl Space	1,915.1	519.2	341.6	-29.9
Sealed Attic	1,998.5	-83.4	188.9	152.7
Net		435.8		122.8
Climate Zone 15				
Baseline	6,521.0		130.8	
Sealed Crawl Space	4,237.5	2,283.5	143.3	-12.6
Sealed Attic	5,953.6	-1,716.1	79.3	64.1
Net		567.4		51.5

[11] Negative values denote energy increases.

Table 35 lists similar regression extrapolations for the Pomona site.

TABLE 35 - ENERGY USAGE AND SAVINGS FOR POMONA BUILDING TYPE IN STUDIED CLIMATE ZONES[12]

Local Weather (within CZ9)		
	HVAC Electrical Energy (kWh/yr)	Electrical Energy Savings (kWh/yr)
Baseline	344.4	
Sealed Crawl Space	280.3	64.1
Sealed Attic	231.0	49.3
Net		113.4
Climate Zone 8		
Baseline	50.0	
Sealed Crawl Space	142.9	-92.9
Sealed Attic	138.0	4.8
Net		-88.0
Climate Zone 9		
Baseline	144.9	
Sealed Crawl Space	187.0	-42.4
Sealed Attic	167.9	19.1
Net		-23.3
Climate Zone 10		
Baseline	303.1	
Sealed Crawl Space	261.0	42.1
Sealed Attic	217.9	43.1
Net		85.2
Climate Zone 15		
Baseline	1,777.6	
Sealed Crawl Space	949.1	828.5
Sealed Attic	683.3	265.7
Net		1,094.3

[12] Negative values denote energy increases.