Diagnostic Performance Assessment of 30 New California Homes

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ABSTRACT

The Residential Construction Quality Assessment project was developed to evaluate how well energy-efficiency measures are installed in new California homes. In Phase I, thirty homes with tight duct systems were tested statewide beginning late summer 1999. Detailed diagnostic testing was performed to assess duct leakage, HVAC system airflow, envelope leakage, and insulation installation effectiveness. Additional data were collected to document features found in these new homes and for comparison to current assumptions in the California Residential Building Standards.

Results indicate that with the exception of duct system leakage, the houses tested did not, as a whole, exceed "industry standard" levels of performance. Tested duct leakage was generally close to required "tight duct" leakage levels, especially if prior HVAC contractor or third-party testing was completed. Otherwise, observed defects were numerous including:

- HVAC system air flow 13% below the industry standard 400 cfm/ton level
- high duct static pressures
- room-by-room air flow deviations from design requirements
- underblown ceiling insulation
- interior walls and building cavities well connected to unconditioned space
- insulation installation defects

Virtually all of these defects are correctable through improved building and design practices, improved contractor training, greater attention to detail, and an integrated "house as a system" construction approach. The benefits of transforming the residential construction industry will include energy and peak demand savings, improved indoor air quality and comfort, reduced greenhouse gas emissions, and reduced builder callbacks and litigation.

Introduction

Building an energy-efficient, comfortable house is a challenging prospect as trends in home design are creating houses with increased architectural complexity such as cantilevered floors, interior columns, arches, and soffits. These features complicate the work of the mechanical contractor, and the framers, insulators, and drywall contractors who should be striving for a single interface uniting the thermal, pressure, and moisture (TPM) barriers between conditioned and unconditioned space. Compounding these challenges, many subcontractors have not received the necessary training to understand the implications of their work and its relationship to the other building trades. Ever-present cost pressures in the construction industry result in lack of attention to areas which may be invisible to the homeowner, but critical to the overall house performance. Examples include low HVAC air flow (due primarily to inadequate duct sizing and leaky duct systems), lack of an adequate TPM barrier (poor draft stopping of interior cavities, open floor systems, etc) and subpar insulation installation.

In recent years, the California Energy Commission (CEC) has worked to improve the quality of residential construction by promoting the use of diagnostic tools and by developing protocols for efficient envelope (Hammon, 1999) and HVAC system design and installation (Modera and Hammon, 1999). To further this effort, the CEC is sponsoring the Residential Construction Quality Assessment (RCQA) project, which involves detailed diagnostic testing on 60 new homes throughout the state. The primary goals of the testing are to use diagnostic tools to assess how well key energy features are being installed, and to evaluate the effectiveness of these diagnostic tools. These tools include duct pressurization devices, blower doors, flow hoods, digital pressure gauges, and the infrared camera. This paper summarizes results from the first of two field test phases. The houses were selected to assess California "leading edge" practitioners who are installing, testing and verifying tight duct systems. Test results from the second project phase (an additional 30 houses) were not available in time for this paper.

Testing focused on the following key issues:

- Cooling system sizing
- HVAC system total air flow and distribution
- Duct system characteristics (surface area, R-value, sealing materials)
- Duct leakage
- Envelope leakage
- Combustion safety
- Identification of the air barrier and problems related to maintaining the barrier

The field data collected are useful in quantifying energy performance, providing valuable feedback on assumptions used in the Energy Commission's modelling methodologies, and investigating the validity of various diagnostic procedures. Field observations also provide useful input on how well envelope and HVAC design and installation protocols address the kinds of problems observed in the Phase I field work

Methodology

The field testing protocol for the RCQA project was developed in conjunction with CEC staff and reviewed with outside parties. The first two test sites represented "trial runs" and included outside experts to participate and comment on the procedures. Procedures were modified after the first two houses and used on the remaining Phase I test sites. Tests and inspections addressed by the protocol include:

- Duct installation inspection (for design, materials used, and installation quality)
- Duct system performance (total airflow, flow by register, and measured leakage)
- Various envelope leakage tests using the blower door
- Visual and infrared camera inspection of insulated walls and ceilings to assess insulation defects (voids, compression, un- or underinsulated areas, etc)

- Visual inspection of similar houses prior to drywall to assess how draft stopping is performed, how the pressure envelope is sealed, and how framing details are handled.
- Photos, videos, and infrared videos to document observed defects and anomalies

This paper focuses on the following key aspects:

HVAC Airflow

Several recent studies (Neme, Proctor & Nadel, 1999; Neal 1998) have documented the impact of system airflow on cooling capacity, operating efficiency, and cooling energy use. Although manufacturer-recommended air flow rates for residential split-systems are typically 350-450 cfm per nominal ton, actual in-situ flow rates have been found to average 327 cfm per ton in a nationwide survey (Neme, Proctor & Nadel, 1999).

Low airflow is a problem for several reasons. If system airflows are below the prescribed 350-450 cfm per ton range, refrigerant charging tables become invalid. Low airflow increases latent cooling, which is largely unnecessary in dry climates like California. In fact, "dry climate" HVAC design should strive for air flow levels exceeding 400 cfm/ton to increase sensible cooling and allow for potential downsizing of the condensing unit (due to the increased sensible cooling capacity).

Cooling System Sizing

To address sizing and air flow issues, the RCQA project performed detailed room-by-room loads analysis using Air Conditioner Contractors of America-approved Manual J software (ACCA, 1986) for each of the test houses, if they were not provided by the contractor. One limitation of Manual J is that the program assumes that the installed ducts are substantially tight. Typical attic cooling system duct losses of 15% (for R-4.2 ducts) represent only conductive duct losses at design conditions. There are two key ramifications to this assumption. First, there is no way for the mechanical designer to take a downsizing credit for tight ducts. Second, if it is presumed that Manual J properly sizes systems, overly conservative assumptions elsewhere in the program must compensate for the 20-30% duct leakage that is part of an industry standard installation.

Duct Leakage

The "Duct Blaster" fan pressurization device has become the standard for measurement of duct leakage. The advantages of using the Duct Blaster are that the tests can be performed quickly and in conjunction with remediation efforts to seal duct leaks. The Duct Blaster pressurizes the entire duct system to a uniform pressure (typically 25 Pa) and determines airflow at the pressurization fan.

Insulation and TPM Barrier Integrity

In colder areas of the country tight, well-insulated building envelopes are essential to insuring occupant comfort and avoiding indoor moisture problems and frozen pipes. In the areas of California where most residential growth is occurring, these concerns are minimized resulting in little attention to the insulation installation details and the proper application of air barriers. To help evaluate these envelope issues, construction anomalies affecting the thermal and pressure integrity of the building envelope leakage were documented on film and on videotape. In addition, detailed visual inspections of identical under-construction homes of the same floor plan were performed to help identify the origins of the anomalies observed in the completed houses.

Results

Phase I testing of the 30 homes was completed in January 2000, with most of the testing occurring from mid-September to mid-December. The geographical range of these homes was from San Diego to Mt. Shasta in Northern California. Results from Phase II testing, completed in early spring 2002, were not available in time for this paper.

House Characterization

Two-thirds of the Phase I RCQA houses were located in California's Central Valley where a significant fraction of new construction growth is occurring. Eight were in southern California and two were in Mt. Shasta. The mean floor area averaged 2,229 ft^2 and ranged from 1,260 to 4,170 ft^2. All houses were slab-on-grade construction, with half being single-story and half being two-story. Fourteen of the 30 houses participated in new construction programs that required duct testing. Six were part of a municipal energy efficiency program where a sampling of installed duct systems were tested, and ten involved voluntary builder efforts to install tight ducts where duct testing was not a required component.

Twenty-eight of the 30 houses had 2 x 4 framed wall construction, with studs nominally spaced on 16" centers; the remaining two houses had 2 x 6 construction with studs on 16" centers. Wall cavity insulation varied from R-13 to R-19 with nearly half of the houses having exterior rigid insulation. Three of the houses used cellulose in the wall cavities. Ceiling R-values ranged from R-19 to R-49, with the six R-19 insulated houses located in southern California.

All houses had split-system air conditioning systems with all but three air handler units located in the attic[1]. Two HVAC systems were heat pumps and thirty were gas furnaces with outdoor condensing units (two houses had two HVAC systems). Two-zone systems were installed in five homes. With two exceptions R-4.2 flex duct was used, predominantly in the attic. One house had R-8 ducts fully installed in conditioned space in hall dropped ceilings, and the second had uninsulated sheet metal ducts installed under the building slab.

Detailed HVAC design methods, such as ACCA's Manual J and D (or substantially equivalent procedures), were performed by the HVAC contractor on 8 of the 30 houses. For production home design work, design loads were based on room-by-room loads analysis for the house orientation generating the highest cooling load. No effort was made to aggressively size the systems. The goal was to determine the design loads if a contractor had properly used the Manual J procedure.

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[1] The remaining three air handlers were located in indoor closets

Cooling System Sizing

Cooling system sizing averaged 569 ft^2 per ton and ranged from 440 to 1,010 ft^2 per ton. (The two CZ16 houses with sizing at over 1,000 ft^2 per ton are highly efficient houses with ducts in conditioned space and guaranteed energy bills.) Interestingly, the houses located in mild Southern California coastal climates had more cooling capacity per ft^2, on average, than the houses located in the Sacramento area.

Since Manual J analysis was either provided or completed for each of the 30 houses, it was possible to compare installed system sizes with the sizes based on Manual J loads. Required equipment capacity was determined by rounding up to the nearest half ton increment. Using this procedure, 19 of the 32 installed systems were found to be properly sized, ten were oversized, and three were undersized. The average oversizing for the 32 installed systems was found to be 0.11 tons, or 3% of average installed capacity. If an additional 15% oversizing is added[2], the average system oversizing is roughly 18%, which amounts to half a ton on systems of 3 tons or more. Under this more realistic scenario, 22 of the 32 systems would be oversized.

HVAC Airflow

On average, the measured HVAC system airflow was 349 cfm/ton, or 12.8% below the industry nominal airflow level of 400 cfm/ton. The eight "contractor designed" systems had average measured total airflow within 1% of that specified by Manual J, while the 23 "non designed" systems were found to be, on average, 15% below Manual J levels.

Early on in the Phase I field work it became apparent that not only was total airflow typically low, but also airflow was poorly distributed within the house. Poor air distribution often results in comfort complaints, which represent a major source of builder callbacks. Figure 1 illustrates the problem by plotting measured airflow versus "target" design airflow for each register. Registers with low flow requirements consistently get too much air at the expense of the rooms with high airflow needs. For houses that did not have detailed design performed, average measured airflow for rooms with high requirements (e.g., master bedroom suite) was found to be 66% of the design flow vs. 88% for "designed" houses.

Duct Leakage

The 30 Phase I houses represented a subset of the "tight duct" homes being built in California. According to the current State Energy Standards, leakage from tight duct systems should not exceed 6% of the system fan flow, which is significantly lower than the 20-30% leakage common to most residential systems.

Mean duct leakage for all 32 systems was 106 cfm at 25 Pa, ranging from 31 to 228 cfm. As a fraction of nominal fan flow, duct leakage averaged 7.7%, ranging from 4.1% to 19.6%. Thirteen of the 32 systems satisfied the 6% leakage target. Nineteen of the 32 systems were previously tested by either the installing HVAC contractor or a third-party tester. On average, contractor-measured leakage was 6 cfm lower than that measured under the RCQA project. Interestingly, three of the houses with "designed" ducts had the highest percentage leakage which may weaken the notion that contractors that design their systems

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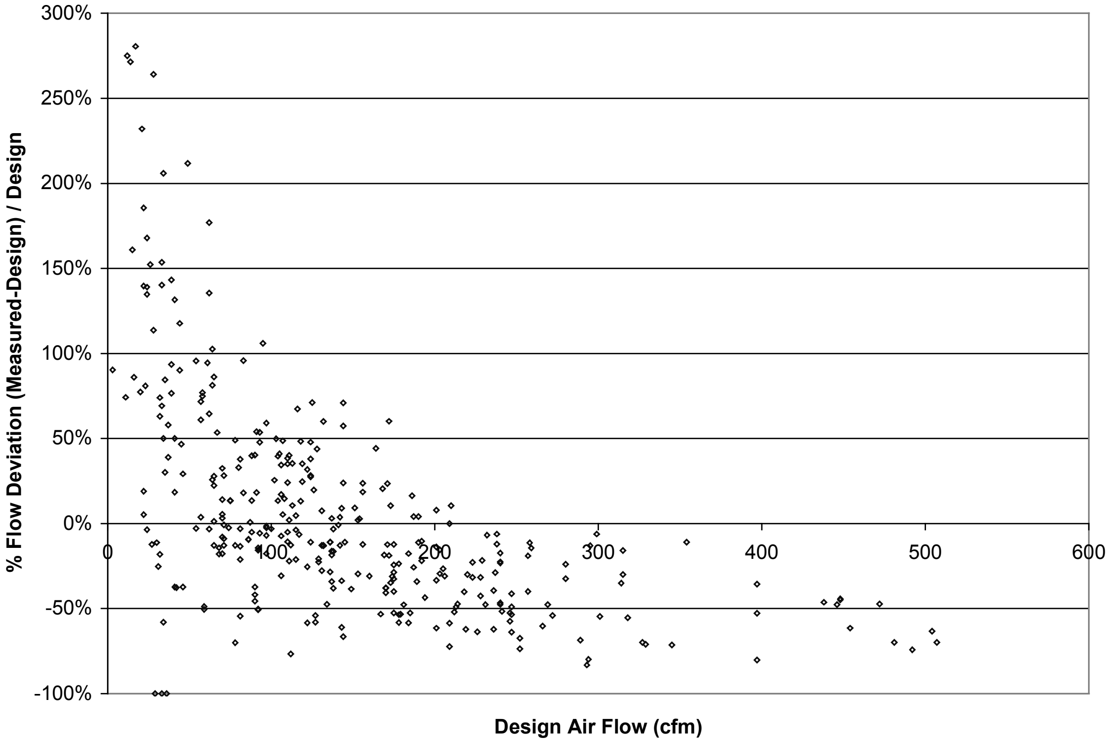
[2] Due to Manual J's inability to recognize the difference between industry standard and tight duct systems.

will also install tight duct systems. Detailed design was not found to be a statistically significant indicator of duct leakage, however prior contractor testing was. RCQA-measured leakage was 39% lower (84 vs. 139 cfm) for those homes previously tested relative to those that were not tested.

On average, 67% of the measured leakage was estimated to be supply leakage. Duct leakage to outside, which is measured with the entire house pressurized to 25 Pa with the blower door, was found to average 83 cfm (or 81%) of total leakage.

Figure 1. Deviation Between Measured and Design Airflows



Envelope Leakage

Both Specific Leakage Area (SLA) and Air Changes per Hour at 50 Pascals (ACH50) are reported in Table 1 for the thirty houses. SLA was calculated by multiplying the measured "cfm_{50}" by a constant (3.819) and dividing by the conditioned floor area in square feet. The average SLA for all but the two houses with guaranteed energy bills was 3.51 in^2/ft^2, which is 20% lower than the average default SLA value assumed in the State Energy Standards for houses with tight duct systems (4.4 in^2/ft^2). A final blower door test was completed at each house with all accessible recessed ceiling lights sealed. Recessed lights leaked an average of 11.5 cfm_{50}, or 0.6% of the average measured house leakage. The average number of recessed lights per house was 9.0, ranging from zero (at eight houses) to a maximum of 40.

Statistical analysis was completed to assess the extent to which the presence of specific features would predict the house's SLA. Factors that were considered included number of stories, wall cavity R-value, wall insulation type, presence of exterior wall foam insulation, ceiling insulation R-value, duct leakage as a percentage of default fan flow, conditioned floor area, number of recessed lights, and presence of a wood burning fireplace. Given the small sample size, only the fireplace was found to have a statistically significant effect on SLA at the 95% confidence interval. One house with a fireplace was tested after the fireplace glass doors were thoroughly taped and sealed. The measured SLA reduction after sealing was 0.72, 23% of the total house leakage.

Table 1. Envelope Leakage Results

Parameter	Average	Maximum	Minimum	σ
SLA	3.51	5.15	1.68	0.82
ACH50	5.5	8.7	2.6	1.64

Figure 2 plots SLA as a function of building floor area and distinguishes between houses with and without fireplaces. The two houses built with special attention to envelope sealing are found at the lower left hand corner (1500 ft^2 and SLA<2). These two were the only Phase I houses where emphasis was placed on insuring an especially tight envelope was installed. Although three of the four houses without fireplaces are among the lowest SLA sites, the fourth is one of the highest. This discrepancy appears to indicate that there are other factors significantly affecting house leakage. In addition to the two 1,500 ft^2 houses, four additional houses were determined to have very tight envelopes with SLA's of roughly 2.0. Three of the four houses were simply constructed with uniform flat ceilings throughout and no soffits or kneewalls. This type of construction is more conducive to proper air sealing and draft stopping than typical construction emphasizing architectural features (e.g. interior columns and arches), varying ceiling heights, and cantilevered floors. There is no clear explanation for how the fourth tight house (3,150 ft^2 and SLA$\cong$2) achieved low envelope leakage.

Table 2 compares calculated SLA values for the five identical house plan pairs tested in Phase I. Interestingly, the SLA difference between "twins" was never less than 12%, and averaged 15%[3]. In three cases, one house of each pair had spray cellulose insulated walls. For two of the three house pairs, the cellulose wall had a lower SLA than the batt insulated wall, although overall there was no statistically significant difference between the batt and cellulose insulated houses.

Table 2. SLA Comparison Among Identical House Pairs

House Pair	SLA Values	Δ%	Comments
1	1.44 & 1.69	17.4%	2nd value for cellulose wall house
2	3.86 & 4.33	12.2%	1st value for cellulose wall house
3	3.64 & 4.10	12.6%	
4	3.70 & 4.35	17.6%	
5	1.68 & 1.93	14.9%	1st value for cellulose wall house

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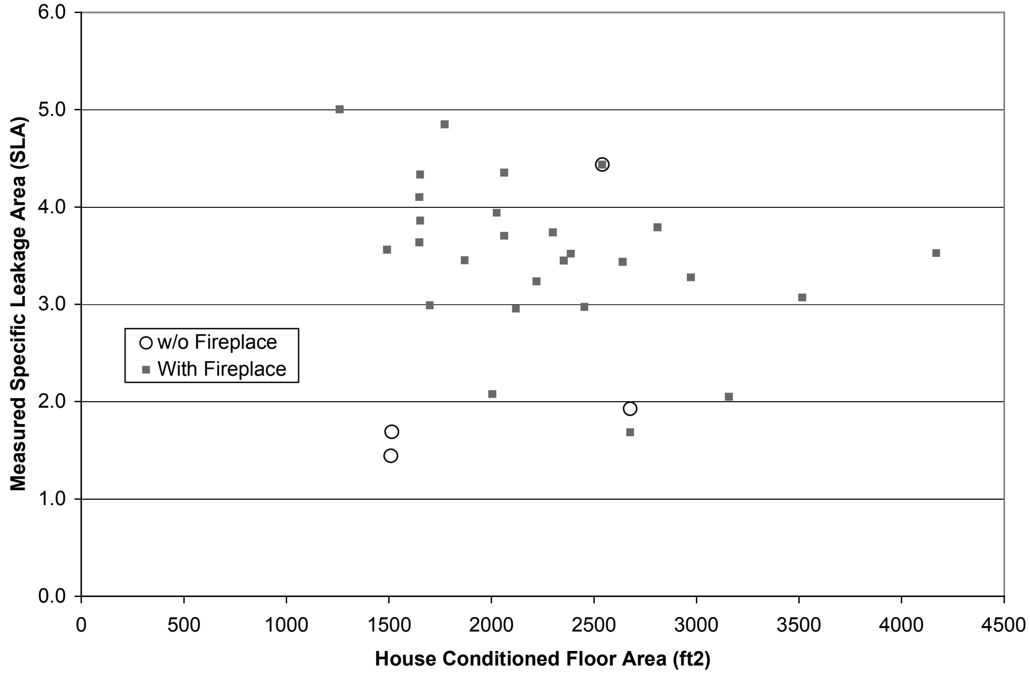
[3] This result supports the hypothesis that random TPM barrier defects are the cause for a considerable amount of envelope leakage.

Figure 2. Measured Envelope Leakage (SLA)



Two-story houses were compared to one-story houses with the expectation that the former would have higher leakage due to interior and cantilevered second floors, which are common sources of leakage. Interestingly, the two-story houses were found to have 7% lower leakage than the one-story houses (3.61 vs. 3.35 SLA). These results may be due to the fact that a greater proportion of envelope leakage can be attributed to the ceiling rather than to the walls. Another factor is that larger houses tend to have lower SLA, since all houses tend to have features in common (fireplace, vertical plumbing penetrations, vent and flue penetrations) whose impact is reduced as house size increases. For the Phase I houses, the two-story houses were on average 35% larger than the single-story houses (2593 vs. 1917 ft^2).

Based on data collected in Phase I, it appears that besides fireplaces, generic construction defects such as penetrations through the pressure barrier (e.g. plumbing, exhaust fans, duct chases), leaky interior wall cavities, and floor systems are prime contributors to house leakage.

Insulation Inspection

The effectiveness of insulation installation is difficult to quantify. Although it is easy to visually verify that installed wall and ceiling insulation levels are consistent with required R-value levels it is difficult to accurately state how well the insulation performs without completing detailed hot-box testing in the laboratory. For the RCQA project, several techniques were used to try to assess insulation installation quality and the level of performance degradation due to defects. For wall insulation, other houses in the subdivision at the insulation stage were inspected, when possible.

Table 3 provides a qualitative assessment of how well individual elements of the California Energy Commission's Envelope Protocols are being followed in the field. These protocols were developed in conjunction with industry experts in 1999 to improve the quality of insulation installation, air sealing, and window installation. Each item in the envelope protocol was "scored" by approximating the frequency that each item was properly completed in the field.

Table 3. Comparison of Field Observations with Envelope Protocols

CIEE Envelope Protocol Item	% Time Properly Implemented
Wall Insulation	
Batts correctly sized to fit snugly at sides and ends	70-90%
Non-standard width cavities with insulation cut 1" wider than cavity	70-90%
Rim joists insulated to wall R-value	70-90%
Kneewalls batts in contact with drywall	70-90%
No stuffing of insulation in non-standard width cavities	40-60%
Minimal insulation compression	40-60%
Tub/shower walls insulated	40-60%
2x6 cavities with R-13 instead of R-19	70-90%
Rim joist insulation cut to fit	10-30%
Exterior wall channels insulated	10-30%
Kneewalls/skylights insulated to minimum R-19	10-30%
Insulation cut to fit around wiring, plumbing, electrical boxes	0%
Skylight shaft batts in contact with drywall	0%
Attic side of kneewall/skylight batts covered by a facing rated to stop attic air intrusion	0%
Ceiling Insulation	
1" free air space between roof sheathing and insulation at eave/soffit vents	100%
Baffles at eave/soffit vents installed to keep insulation from blocking vents	70-90%*
Non-IC fixtures boxed and insulated	70-90%
Insulation covering all IC rated light fixtures	70-90%
Blown insulation installed uniformly and to required thickness	40-60%
Draft stops in place over all deep drops and interior wall cavities to stop air movement	10-30%**
Attic access insulated with rigid or batt insulation	10-30%
Ceiling batts cut or split to fit around wiring and plumbing	0%
Caulking and Sealing Procedures	
Top plate penetrations sealed	100%
Weather stripping at exterior doors	100%
Continuous sealing at bottom plate	40-60%
Weather stripping at attic access	10-30%
Sealing around tub and shower drains to the floor	10-30%

* baffles often poorly installed & do not prevent wind from blowing insulation from vents

** building code compliant draft stops are often in place, but rarely are they air tight

In terms of wall insulation, it can be concluded from both the visual and the IR records[4] that the basic task of filling a wall cavity with insulation seems to be performed much better than the details which pertain to kneewalls, skylight shafts, and infiltration

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[4] The visual observations of pre-sheetrock homes of the same models as the homes where IR camera work was done indicate more extensive defects in typical installation of wall insulation.

mitigation for exposed batt insulation. These details require more time and attention and are therefore often overlooked by the insulation contractor who is under pressure to quickly complete his work.

Ceiling insulation was visually inspected. For batt insulation, R-value was determined based on batt thickness and labeling. For blown insulation, insulation depth was recorded at a minimum of three locations in the attic to account for variations in insulation depth. Average depth was compared to the required depth based on the type of blown insulation. For the 26 houses where blown-in attic insulation was installed, insulation depth averaged 93% of the required depth. Five houses had less than 80% of the required depth, while 8 houses had more than the required depth.

The Envelope Protocols are a valuable and effective tool in conveying the key steps required to install an effective building envelope. What is lacking are the tools for the framers, insulators, and drywall workers to handle nuances which relate to draft stopping. Visual rendering and field training are essential in transferring this information to the workers in the field.

Building Cavity Depressurization

The goal of the building cavity depressurization studies was to measure cavity pressures at as many accessible locations as possible while depressurizing the house to 50 Pa with respect to outdoors. Areas commonly tested included fireplace chases, duct chases, the wall cavity behind the HVAC thermostat, floor systems, under stairs, house architectural features (columns, arches, pillars, and soffits), and other interior wall cavities. Ideally, if the cavities were fully within the house pressure envelope, the measured pressures would be zero. The closer the pressure is to 50 Pa, the greater the thermal "communication" between the uninsulated cavity and unconditioned space. Maintaining all conditioned space within the house pressure envelope is important not only from an energy perspective, but also from a moisture and indoor air quality viewpoint.

Table 4 summarizes the mean recorded pressures for each of the identified elements. Most of the cavities, with the exception of the wall area behind the thermostat and under the stairs, are closer to outdoor conditions than indoor. Fireplace and duct chases were, on average, most connected with outdoors. Although these results clearly indicate a strong thermal connection to outdoors, they do not quantify the magnitude of the connection. Many factors affect how these cavities interact with conditioned and unconditioned space.

Table 4. Mean Cavity Pressures During House Depressurization

Location	Mean Pressure (Pa)	Std Deviation
Fireplace Chase	32.2	10.0
Floor System	26.5	7.3
Thermostat	21.5	11.4
Under Stairs	17.7	11.6
Duct Chases/Drops	32.9	7.6
Architectural Features	29.5	10.2
Other Interior Walls	30.7	14.3

Conclusions

Overview

An integrated "house as a system" approach to production home building is needed to improve the energy performance and comfort of new homes in California. Currently the various subcontractors typically work independently of one another with little knowledge of the impact their work has on overall house performance. For example, the plumber or electrician may punch gaping holes in draftstopping that the framer has carefully installed. Duct chases, interior columns, and other wall cavities are often open to unconditioned attic space. The result is that in general the TPM barrier is not being installed in a continuous manner resulting in degraded thermal performance.

The HVAC contractor is ultimately left the responsibility of insuring that comfort is met. From their perspective, they need to plan on some level of envelope defects within each house. Load calculations are fine, but they don't handle the anomalies known to exist. Rule of thumb sizing methods provide sufficient accuracy and save time in the bidding process. Oversized equipment is often installed, but with problems (including low airflow, poor air distribution, incorrect refrigerant charge) which reduce system capacity and efficiency. If comfort complaints occur, increasing the cooling capacity is the most common response.

Despite the observed deficiencies, it is important to note that there are many well intentioned builders and contractors committed to building quality homes in California. We found numerous examples of tight duct systems, good HVAC airflow, tight building envelopes, etc. Putting it all together is the hard part and requires diligence from the field supervisors. Improved training protocols and HVAC design tools, field training of subcontractors, tighter builder bid specifications, increased compensation for subcontractors (whose #1 priority has become speed), and third party verification are all necessary elements in improving the performance and comfort of new homes in California.

Specific conclusions by topic area follow:

Cooling System Sizing

Cooling system sizing for the 30 houses averaged 569 ft^2 per ton and ranged from 440 to 1,010 ft^2 per ton. Two exemplary houses, sized at over 1,000 ft^2 per ton with guaranteed space conditioning bills, are indicative of what can be achieved with a "house as a system" approach. Manual J sizings were completed as part of the project to determine proper equipment sizing. On average, cooling system oversizing was found to be 18% of nominal sizing.

System Air Flow

HVAC system air flow for the 30 houses averaged 349 cfm per ton, or 13% less than the industry standard of 400 cfm per ton. The value of detailed HVAC design was evident in that the eight systems that were "designed" were found, on average, to provide total supply air flow equal to the Manual J design requirement, while the "non-designed" systems were found to be an average of 15% low. Six of the non-designed systems had measured airflows more than 20% less than the design requirement. Design air flows approaching 450 cfm per ton are more appropriate in California's dry climate regions. One HVAC contractor in the project regularly upsizes the air handler relative to the outdoor unit to achieve higher airflow per ton of installed cooling.

Duct Leakage

Average measured duct leakage was found to be 7.7% of system fan flow, or 28% higher than the CEC's tight duct target of 6%. Seventeen of 32 systems met the leakage requirement of the program they were participating in, while 13 met the 6% target. The 19 previously houses tested by the installing HVAC contractor (or a third party tester) were tighter than the homes that were not tested supporting the value of testing each home. Although duct leakage varied with different sealing methods, no statistically significant difference in duct leakage could be attributed to the sealing materials used.

Envelope Leakage

Blower door leakage tests revealed an average SLA of 3.51 in^2/ft^2, or 20% lower than the CEC's default assumption for houses with tight ducts (4.4 SLA). Three of the 30 houses exceeded the 4.4 SLA level. Recessed light leakage was found, on average, to be 5.4% of average house leakage. Statistical analysis was completed to assess the extent to which the presence of specific features would predict the house's SLA. Given the small sample size, only the fireplace was found to have a statistically significant effect on SLA. Based on field observations, anomalous penetrations in the TPM barrier appear to be key contributors to overall envelope leakage.

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