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Measured Air-Tightness and Thermal Insulation Quality of 11 Industrialized Houses

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Abstract

Building air-tightness and thermal insulation quality has been evaluated for five major industrialized housing manufacturers in the U.S. A small sample size of 11 houses has been tested to date. The sample includes factory stud-frame panelized, foam core panel, and modular construction. Reference air-tightness numbers such as air change rate at 50 Pascal pressure difference, effective leak area, equivalent leak area, and specific leak area are reported. For the houses with forced air distribution systems, a duct leakage and house pressure balance analysis was also conducted. Special attention was paid to the air distribution system and its impact on energy efficiency, health, safety and durability. Thermal insulation quality was evaluated using an infrared imaging system. Infrared images showing conduction through framing components, misplaced or missing insulation, convective air paths which short circuit insulation, air leakage in marriage walls and duct leakage are presented.

Introduction

The Energy Efficient Industrialized Housing (EEIH) project, sponsored by the U.S. Dept. of Energy, seeks to help industry increase the energy efficiency of its products and increase its productivity. One of the ways industry can take advantage of the EEIH project by participating in a short but intensive two-and-a-half-day Process and Energy Efficiency

Review (PEER) visit. It was in the context of the PEER procedure that the results reported here were obtained. Typically, between six and nine members of the EEIH project team visit the industrialized housing manufacturer. On the morning of the first day of the PEER visit there is an introductory briefing by the EEIH team and the housing manufacturer, followed by a plant tour. By early afternoon of the first day, the team's energy, manufacturing and design groups split up and begin work in their specific task areas. The energy group tests model homes for thermal insulation quality and building air leakage, using an infrared scanning system and a blower door. The manufacturing group evaluates areas such as labor productivity, materials handling, inventory management and manufacturing methods. The design group performs an assessment of design and marketing methods. Day two is a continuation of work in the separate task areas. The PEER visit concludes on the third day after a two-hour exit briefing with the CEO and senior management. Recommendations are made and discussed in each of the energy, manufacturing and design areas. A written report follows.

On the average, houses are much more air tight than they were a decade ago (Palmiter et al., 1991). Advances in materials which let moisture pass through while providing great resistance to air flow have made "air barriers" commonplace in building construction. Increased consumer and builder awareness through education has contributed greatly to reducing the energy lost by air leakage in houses. There are still issues remaining, however, and some just recently coming to the forefront, such as the effect of air distribution systems on energy use, occupant health and safety, and material durability . A remaining issue is that of air quality (Tsongas et al., 1992)--just how tight is too tight to maintain good air quality throughout a house, and what is the definition of good air quality? Can the meaning of good air quality be effectively quantified? Typically, the driving force behind ventilation in housing has been to either meet the prevailing ASHRAE recommendation of 0.35 air changes per hour (ASHRAE, 1989), or to provide enough ventilation to avoid obvious moisture problems in the house. Some builders are afraid to take extra care to air tighten a house since they may be forced to deal with ventilation issues which could increase the cost of their product too much. Dealing with the problem from a moisture control view point, others are reluctant to install vapor retarders on ceilings, stating that they would rather let excess moisture migrate through the entire ceiling area to the attic, where it may not have a deleterious effect for a long time, rather then get a call-back due to condensation on windows or moisture damage to drywall at poorly insulated locations. These fears are understandable when so many houses are constructed by small companies trying to make a modest profit and often-times utilizing whatever labor help is available. Housing manufacturers, however, through advanced process control, a more stable and experienced work-force, and the economy of scale, should be able to set aside these fears and produce energy efficient houses knowing that the houses will function properly as complete systems.

A systems approach to constructing houses takes into account how the different building components should work together instead of working against each other. For instance, air leakage paths can completely short circuit insulation, regardless of the R-value, rendering it ineffective. The major system components in a house which affect energy efficiency are: the weather resistant skin, the insulation (thermal) envelop, the structural envelop, the interior finish skin, house wiring and plumbing, ducts, air circulation fans, exhaust devices such as bath and kitchen fans and dryers, combustion appliances, interior doors, recessed light fixtures, and the list could go on. The systems approach to house construction is difficult to achieve when so many different trades and independent companies are involved as they are in the site building process. Even when the building codes are strict, code enforcement is the limiting factor; many people performing this important task are part-time and lacking in sufficient experience or education. In the industrialized housing process, more concentrated focus can be placed on the house as a system, and more experience and resource can be applied to assure that anticipated goals become a reality.

Test Procedure

The energy evaluation group of the PEER team tries to look at houses to be tested with an eye for how the building works as a system, especially with regard to pressure imbalances within the house and relative to outdoors. With a minimum 10oF steady state temperature difference, indoors to outdoors, an initial infrared scan was performed on the inside surface of the building thermal envelop. This initial scan indicated any irregularities that existed in the thermal envelop under normal pressure conditions. To simulate elevated pressure influences such as wind, stack and exhaust devices, a fan pressurization unit, or blower door, was installed in an exterior door opening and used to bring the house to about 15 to 20 Pa below the outdoors. As outdoor air was being sucked through all cracks and leaks in the thermal envelop, another infrared scan was performed. This scan clearly showed the presence of air leakage paths and how they were affecting the thermal envelop and ultimately energy use. After locating general areas of air leakage, the leaks were often be pinpointed by reversing the blower door fan, pressurizing the house to about 15 Pa above outdoors, and using a chemical smoke generator to indicate leak locations.

A multi-point blower door test was performed, with all of the air distribution ducts open to the house, to obtain several reference air leakage numbers. These include: air leakage at -50 Pa pressure relative to outdoors (CFM50), air change rate at -50 Pa (ACH50), effective leakage area (ELA) at 10 Pa, equivalent leakage area (EqLA) at 4 Pa, specific leakage area (SLA), and an estimate of the natural air exchange rate. The estimate of natural air exchange was calculated two ways, using the models developed by Sherman and by Persily (Meir, 1986). A second multi-point blower door test was performed with all air distribution ducts taped off. This test allowed a calculation of duct leakage, separate from building leakage, by taking the difference in CFM50 between the first and second tests. Since 50 Pa is about 0.2 inch of water column, the difference in CFM50 is a realistic estimate of air leakage at operating conditions in ducts.

One stud-frame panelized house was tested for air infiltration more extensively than the others, using sulfur hexafluoride (SF6) tracer gas. Tracer gas was injected into the return air of the air distribution system and the decay of tracer gas, by dilution, was measured over time. The natural air exchange rate was calculated as the slope of the log10 of the SF6 concentration to the time interval. The tracer gas test was performed twice, with the air handler on and off. This gave an indication of the increase in air exchange with the outdoors due to the air handler operation.

Additional testing was performed to ascertain the effects of the air distribution system and exhaust devices and interior door closure on the pressure balance inside the house and relative to the outdoors. This testing took into consideration energy use, occupant heath and safety, and material durability. Energy use may be increased if some areas of the house are pressurized relative to outdoors and other areas are depressurized increasing the air exchange rate. Health and safety may be affected due to the possibility of combustion products back-drafting into the home, or the possibility of flame roll out from combustion appliances, or increased entry of radon. Material durability can be affected due to the possibility of moisture laden air coming into contact with cold surfaces and condensing inside walls or ceilings causing mold, mildew and rot.

RESULTS

Blower Door

In all, 11 houses were tested for a total of 5 industrialized housing manufacturer's. These industrialized house types include: modular, stud-frame panelized, and foam core panel. In addition, two HUD code homes have been tested in cooperation with the National Renewable Energy Laboratory (Juddoff et al., 1992). Table 1 gives the reference leakage numbers for all of the houses tested by the blower door method. ELA and EqLA describe the hole area that would exist if all cracks and leakage openings of the house were gathered into one location. ELA is the effective leak area that would exist at a house pressure of -4 Pa. EqLA is the equivalent leak area that would exist at a house pressure of -10 Pa. CFM50 is the air leakage at -50 Pa. ACH50 is the air change rate at -50 Pa. ACH50 divided by 20 gives an unadjusted estimate of the natural air change rate as proposed by Persily. The factor N was developed by Sherman to adjust for climate, building height, exposure to wind, and size of leak cracks. ACH50/N then gives an adjusted estimate of the natural air change rate as proposed by Sherman. SLA is the specific leakage area, which normalizes the ELA by floor area.

Table 1
Summary of Blower Door Test Results

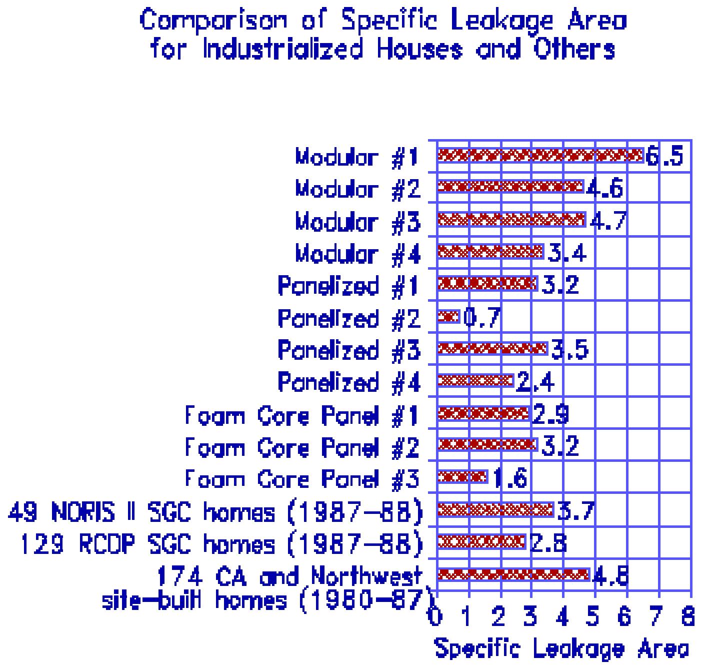
	Mod	Mod	Pan	Pan	Foam	Foam	Foam	Modr	Mod	Pan	Pan
floor area	1500	3500	2800	4876	1,850	1,550	1260	2186	1776	3030	2600
volume	11.5K	35.8K	26.1K	51.2K	15.4K	14.8K	12.2K	17.5K	14.2K	24.2K	20.8K
ELA (in^2)	140	230	128	50	77	72	29	149	88	152	91
EqLA (in^2)	‡	‡	279	104	143	137	56	261	161	279	174

EqLA (in^2)	‡	‡	279	104	143	137	56	261	161	279	174
CFM50 (ft^3/min)	2550	4173	2391	1280	1336	1332	568	2216	1500	2586	1733
ACH50 (1/hr)	13	7	5.5	1.5	5.2	5.4	2.8	7.6	6.3	6.4	5.0
ACH50/20 (1/hr)	0.65	0.35	0.28	0.08	0.26	0.27	0.14	0.38	0.32	0.32	0.25
N	‡	‡	14.8	18.1	25.90	16.65	27.97	16	16	16	16
ACH50/N (1/hr)	‡	‡	0.37	0.08	0.20	0.33	0.10	0.48	0.40	0.40	0.31
SLA (ft^2/ft^2)	6.5	4.6	3.2	0.7	2.9	3.2	1.6	4.7	3.4	3.5	2.4
Duct Leak CFM50 (ft^3/min)	168	†	‡	†	†	26	†	742	121	32	34

† No central air distribution system
‡ Not available

The Bonneville Power Administration's Super Good Cents (SGC) program and Long-term Super Good Cents programs specify no greater than 7.0 ACH50 to meet the air leakage standard. As can be seen in Table 1, all houses tested, except Modular #1, would meet the SGC standard for air leakage. The ASHRAE recommendation is 0.35 air changes per hour at natural pressure conditions. When using the ACH50/20 model, all houses except two, Modular #1 and Modular #3, meet the recommendation. When using the ACH50/N model, three houses do not meet the recommendation. For houses that are more air tight than the ASHRAE recommendation, a whole house mechanical ventilation system should be considered. A mechanical ventilation system may be as simple as operating kitchen and bath fans by an automatic timer perhaps with ventilating windows, or as complex as a two-direction heat recovery ventilator ducted to all rooms. In cold climates, a heat recovery ventilation system may be economical, whereas in less severe climates, a single-direction exhaust only system with passive make-up air vents may be more cost effective (Wahlstedt, 1991). Certainly, whatever ventilation strategy is taken, one must take house pressure conditions into account, especially if combustion appliances are present. Also, field research shows that many occupants turn off their ventilation systems because of noise or cold drafts or to reduce energy use. In a recent report of a study conducted in the Northwest (Tsongas, 1992), a majority of house ventilation systems were not working as well as expected or were not being used by the occupants. This resulted in numerous moisture-related problems due to inadequate control of high indoor relative humidities. More research should be conducted to develop effective mechanical ventilation systems for housing.

SLA is the only reference number shown which normalizes by floor area. Figure 1 shows a comparison of SLA for all houses tested compared to houses used for studies in the Northwest and California *(Palmiter et al., 1991).*



Using a chemical smoke generator to pinpoint the cause of air leakage, several common problem areas were evident. The highest occurrence of leaks were found at:

- wall base plate and band joist areas;
- wiring and plumbing penetrations through floors and ceilings;
- recessed canister lights;
- building cavities used as part of the air distribution system (return or supply plenums).

Duct Leakage and Pressure Balance

The last line in Table 1 gives the air leakage in the forced air distribution system (duct system) at a reference pressure of 50 Pa (Duct Leak CFM50). Based on research in Florida, it should be reasonable to get less than 100 CFM50 leakage in a duct system (*Coyne*, 1992). Of course, it is possible to have zero leakage in a duct system but the accuracy of diagnostic tools, and cost effectiveness criteria, may be limiting factors. Of the eleven industrialized houses tested, only seven of them had a forced air distribution system. Of those seven houses, three had less than 100 CFM50 duct leakage; two were stud-frame panelized houses and one was foam core panel. Three modular houses had duct leakage between 121 and 742 CFM50.

Notable duct system leaks or other problems were found as follows:

- loose or unsealed duct-to-floor connections;
- taped seams instead of fiberglass mesh and mastic;
- interstitial building cavities used as return plenums;
- unsealed flex duct connections to rigid fiberglass boots or plenums (use fiberglass mesh and mastic in addition to tie wraps)
- uninsulated metal connectors for flexible ducts--this could cause condensation and energy loss problems;

In one stud-frame panelized house, additional infiltration testing was conducted using SF6 tracer gas. One test was conducted with the air distribution fan operating and resulted in an air infiltration rate of 0.68 air changes per hour. A second test was conducted with the fan off and resulted in an air infiltration rate of 0.36 air changes per hour. The difference between these two results indicated that pressure induced air infiltration, due to operation of the fan, increased the house air exchange rate by 89%.

Even if the entire air distribution system is within the conditioned space, duct leakage and restricted return air flow paths can still cause problems. Pressure imbalances can increase the house air infiltration rate while the system fan is operating, and can cause portions of the house to be uncomfortable. Pressure balance testing involves measuring pressure differentials between the outdoors and the main body of the house, and pressure differentials between closed rooms and the main body of the house (Tooley et al., 1991). This type of testing is especially important if there are combustion appliances in the house which do not have sealed combustion chambers. The operation of any indoor natural draft combustion equipment, that which relies on non-mechanical intake of inside air to vent combustion products, can be seriously affected by negative pressures created by air distribution and air exhaust systems. It is not uncommon to find that the main body, basement, or utility room of a house can depressurize to -3 to -6 Pa due to duct leakage, exhaust fans, and restricted air flow. At these negative pressures, most natural draft equipment will show signs of improper operation or failure, including back-drafting and flame roll-out.

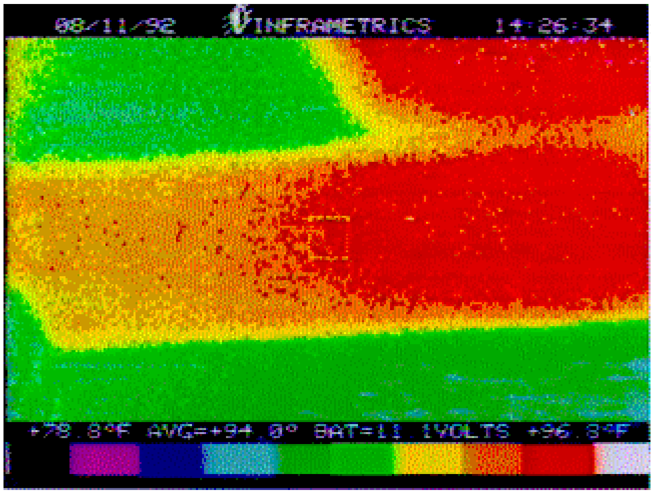
The durability of materials used to construct a building can also be affected by leakage in an air distribution system. For example, if supply duct leaks are dominant in a house then the main body, where the largest return usually is located, will depressurize. If that house is being cooled in a humid climate, then moist air will be pulled into the walls and ceilings possibly causing condensation on the back side of interior wallboard. If, for example, the reverse is true, that is there are dominant return leaks pressurizing the house while the house is being heated in a cold climate, then moist air will be forced through walls and ceilings potentially causing condensation on cold surfaces within the structure. Restricted air flow from closed rooms to the main body will also cause pressurization of the rooms.

The following list gives the more notable findings from the pressure differential testing, along with possible solutions:

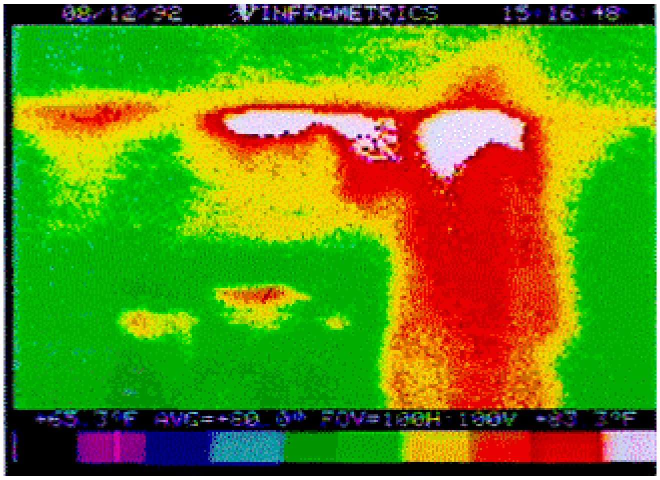
- Depressurization of the house main body to -8.5 Pa with the furnace fan and kitchen and bath exhaust fans on, and the interior doors closed. Presented potential problems with combustion safety, infiltration, and comfort. Solution: Provide separate returns or transfer grilles to closable rooms.
- Oversized return (or undersized supply) in bedroom causing the room to depressurize to 4 Pa. Presented potential problem during humid cooling season. Solutions: Properly size ducts, or add transfer grille.
- Return and supply duct leakage in basement. Presented potential problem of combustion safety. Solution: Seal all return and supply ducts in the basement.
- Three bedrooms in one house pressurized to between 8.5 and 11.5 Pa with the furnace fan and exhaust fans on and interior doors closed. Presented potential problems with wintertime condensation inside structure, increased infiltration, and comfort. Solution: Provide separate returns or transfer grilles to closable rooms.
- Clothes dryer could depressurize a relatively tight house to -3 Pa. Presented a potential combustion safety problem. Solution: Provide make-up air for the exhaust appliance.
- Basement depressurized to -6 Pa due to insufficient return air flow area to the basement furnace fan. Presented potential problem with combustion safety. Solutions: Increase return air flow to basement; provide vents for combustion and dilution air per National Fire Protection Agency Code NFPA 54 for Confined Spaces.

Infrared Imaging

Through infrared imaging, irregularities and defects in the thermal envelop of the house were detected. Figure 2 shows how ceiling insulation was completely missing over part of a second floor bedroom and stairwell in a modular house.



Air leaks in marriage walls of modular houses may be common but are easily corrected with foam sill sealer, high quality caulk, or polyurethane foam when pulling the units together (Pudget, 1991). Figure 3 illustrates how hot attic air was leaking into a marriage wall, short circuiting the thermal envelope.



Thermal shorts in walls can be especially obvious when comparing the thermal image of a stud framed wall and a foam core panel wall. This is illustrated in Figure 4.(a) and (b). The more conductive wood framing shows up as a cold area, potentially allowing moisture problems to develop in exceptionally cold climates.

insert figures 4(a) and 4(b)

Energy loss due to duct leakage can be a significant factor in residential energy use. In a study in Florida *(Cummings et al., 1991)*, the average percent reduction in energy use by repairing leaky ducts was 17%. Figure 5 shows an example of duct leakage, which was found by infrared imaging, in one of the modular houses tested. It shows 56oF air leaking out of a duct located in a hot attic.

Other common findings using infrared imaging include:

- Convective heat flow where ceiling insulation was bulged up near the eaves allowing air movement between the insulation and the wallboard;
- Conduction heat flow where ceiling insulation was not full thickness at the eves;
- Heat flow due to air leakage through tongue and grooved wood ceilings;
- Air leakage between the finished floor and the baseboard due to insufficient air tightening of the wall base plate and band joist area;
- Air leakage from the exterior through framing cavities connected to return air plenums which were not air sealed;
- Air leakage from the exterior through unsealed interior soffits and spaces behind cabinets;
- Improperly insulated knee walls;
- By-pass of insulation due to air leakage through recessed ceiling lights;
- Air leakage through electrical wiring penetrations, especially where insulation was compressed behind wiring;

Conclusions

To our knowledge, this is the first time data has been reported on air-tightness and thermal insulation quality of modular, stud-frame panelized, and foam core panel housing in the U.S.A. The limited data indicates that panelized and foam core houses are being constructed with better air-tightness compared to conventional site-built houses. It seems that modular homes do not yet attain the full potential of greater energy efficiency possible with factory construction. The tests pinpointed the energy loss areas both visually and through measurements, demonstrating the room for improvement to the manufacturers. As a result, some have made changes or are in the process of making changes which when multiplied many times over in the factory environment can have a substantial impact on the quality of houses being constructed today.

Future Work

A side-by-side study of a foam core panel house and a conventional stick-frame house is currently being conducted to further quantify the performance difference between conventional and industrialized housing. After collecting construction and cost data, air-tightness and thermal insulation quality testing will be conducted, followed by short-term energy use monitoring.

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