Field Measurements of Heating System Efficiency and Air Leakage in Energy-Efficient Manufactured Homes

Bob Davis, Jeff Siegel, and Larry Palmiter, Ecotope, Inc.

Detailed field measurement of air leakage and electric forced-air heating system efficiency in nine Pacific Northwest manufactured homes built to adapted Model Conservation Standards were conducted during the 1994 and 1995 heating seasons.

The research measured directly both heat delivery efficiency and system efficiency (as defined by ASHRAE in its *HVAC Systems and Equipment* Handbook) with a short-term alternating coheat test. For this test, a home is alternately heated with the furnace and then with an array of small electric heaters placed in each room which has a supply register. The test switches between these two methods every two hours, recording temperature and energy usage data every ten seconds. An automated control algorithm controls the furnace and coheaters to keep the home at essentially the same temperature during the eight hour test.

A blower door test and duct tightness test are also performed, as are a tracer decay test (to measure effective ventilation rates with the air handler on and off) and other measurements.

The homes performed better than contemporary site-built homes (24 of which were tested with the same protocol during 1991–1993), but system efficiency losses were still substantial, on the order of 20% of the annual heating load.

INTRODUCTION

During the past fifteen years, organized energy conservation efforts have focused primarily on building shell and air sealing measures, including improved insulation levels and better windows. Researchers and sponsors of conservation programs have only recently shifted their attention to ducted heating systems and their effect on overall energy usage in the home. Research results have suggested that duct air leakage, duct conduction losses, and increased air infiltration due to the furnace air handler operation can increase energy usage by 10–40%.

Most research on this subject has been published in the last five years. This research has focused on site-built homes. The research summarized in this report examines heating distribution systems in new manufactured homes. Manufactured homes are built in sections in a production factory and transported via road to the site. Construction specifications (including insulation specifications) for these homes are written by the federal Department of Housing and Urban Development (HUD) and generally enforced by state agencies.

The homes in this study are built to energy-efficiency standards considerably more stringent than the minimum HUD requirements (HUD 1994). The standards were codified under the Manufactured Housing Acquisition Program (MAP), a $100 million conservation acquisition program paid for by Pacific Northwest utilities and the Bonneville Power Administration (BPA). Between April, 1992 and June, 1995, all electrically heated manufactured homes in the Pacific Northwest were constructed to these standards. Manufacturers signed an agreement with BPA and were paid cash incentives to build homes to the MAP specifications.

The field measurements described in this report address the performance of nine of these homes. A number of the measurements are familiar to energy researchers, such as blower door and duct tightness results. A short-term term alternating co-heat test, as conceived by Larry Palmiter (summarized in Olson et al. 1993), is the primary focus of the research. During this test, the home is heated alternately with the forced-air electric furnace and with zonal electric heaters under automated control. The test compares the energy needed to keep the home at the same interior temperature when the heating method is alternated between the forced-air electric furnace and an array of portable electric heaters.

SITE CHARACTERISTICS

Nine homes were tested with the field protocol. Five homes are sited in western Washington. Home M01 is sited at an elevation of 1750 ft^3, just east of the Cascade mountain crest. Homes M07, M08, and M09 are sited in Boise, ID. The average home size of 1434 ft^2 is close to the regional average size for MAP homes (1406 ft²). Double-section homes are by far the most common type of home built to MAP specifications, making up 75% of all MAP homes. The average size of a MAP double-section home (based on manufacturers' records) is 1424 ft² (Baylon et al. 1995).

These homes are factory-built in sections roughly 14 feet wide and 50–60 feet long. A "double-section" home thus consists of two sections which are mechanically fastened after transport. The homes are usually framed with conventional 2×6 wood studs, built atop a steel undercarriage which can be outfitted with axles for transport to the home site.

Fiberglass insulation blankets are draped over the steel undercarriage, and wooden floor joists, usually running perpendicular to the steel I-beams, are placed on top of this blanket. In the most common floor insulation strategy, the floor insulation consists of three R-11 blankets, and the insulation is slit so that it can be brought into the joist cavities outboard of the main steel I-beams. In a notable exception to this construction strategy, (the longitudinal floor), the floor to joists are framed parallel to the steel understructure and each trunk duct runs inside a single joist cavity. All other joist cavities are insulated with two R-11 batts, and another R-11 batt is placed on top of the steel frame before the floor is framed. Site M04 is the only home in this study with a longitudinal floor. In all homes, trunk ducts are wrapped with R-5 fiberglass insulation. Underneath the entire floor structure, there is a continuous nylon barrier called the belly board which protects the insulation and framing members.

The remainder of the house is insulated to standards equivalent to Pacific Northwest site-built codes, namely, R-21 walls with insulated headers and minimized framing lumber, R-38 vaulted ceilings or R-49 attics. The windows used perform on average to a U-value of 0.40 or better, and overall glazing area averages about 12% of the heated floor area.

The heating plant for these homes is a downflow electric furnace installed in a louvered cabinet inside the home. There is no ducted return system, although some furnaces receive ducted outside air through passive or ducted make-

Table 1. *Test Home Characteristics*

Site ID	Location	Width	Floor Area [ft²]	House Volume [ft³]	Site Altitude [ft]	Duct Length [ft]	Trunk Duct Material	Furnace Capacity [kW]
M01	Blewett, WA	Double	960	7561	1750	88	Duct board	11.6
M02	Graham, WA	Double	1716	14586	530	135	Metal	15.2
M03	Langley, WA	Triple[1]	2038	18530	50	145	Metal	19.2
M04	Vashon, WA	Double	1709	14813	250	150	Metal	11.2
M05	Snoqualmie, WA	Double	1699	14144	425	142	Metal	15.2
M06	Everett, WA	Double	1739	14900	350	135	Metal	15.2[2]
M07a/b[3]	Boise, ID	Double	1340	11334	2830	115	Metal	21.6
M08	Boise, ID	Single	858	6280	2710	56	Metal	16
M09	Boise, ID	Single	846	6551	2710	52	Metal	16
Average	—	—	**1434**	**12078**	**1289**	**113**		

[1]Has additional section containing family room and master bedroom.
[2]Nominal rating; only two elements (supplying about 8 kW) connected when tests run.
[3]Two tests were run at this site.

up air systems; metal trunk ducts on each side of double width homes are connected by a large-diameter (usually 12") round insulated flex duct called the cross-over duct. In most cases, the trunk ducts, boot risers, and boots are constructed of 18-gauge aluminum, and are fabricated on site.

FIELD PROTOCOL

Reviewers first perform a detailed walk-through audit of the home, noting furnace and air handler fan specifications and measurements, duct length and insulation, duct defects, and the condition of the cross-over duct, which supplies heat from the furnace to other home sections in multi-section units.

House air-tightness is measured with a two-point depressurization blower door test. Duct tightness is measured with a smaller blower door designed for this purpose. The home's effective ventilation rate (rate of pollutant removal) is estimated with a tracer gas decay test. The test is also performed with the air handler fan running to investigate the increase in infiltration rate caused by the interaction between natural and mechanical infiltration.

The heating system efficiency test ("alternating coheat test") lasts for a total of about eight hours, during which time temperatures and electricity usage are almost continually monitored by thermocouples and a clamp-on power meter and stored by standard data acquisition devices. For this test, portable space heaters ("coheaters") are placed in every room with a supply register, and the house is alternately heated with these heaters and with the furnace during two hour intervals.

The measurements taken during this test allow a comparison of furnace cycling efficiency (which is defined as the average power delivered through the registers divided by the average power supplied at the furnace plenum when the air handler is operating) with the overall heating system efficiency (which accounts for all heat delivered to the living space, including heat recovered from the ducts and crawl space during furnace off-cycles). These efficiency measures are discussed in more detail later in the report.

The homes are unoccupied during the tests, which run on automated control. The test is also run overnight, to minimize solar effects. The data analysis accounts for short-term thermal mass effects when switching from heating with the furnace to heating with coheaters.

Supply register and furnace air handler flows are measured with the furnace operating. The flows are corrected to standard cubic feet per minute (SCFM). The standardized flows are multiplied by measured flow temperatures to calculate the total useful heat delivered to the conditioned space during furnace cycling periods.

AIR LEAKAGE RESULTS

A number of different testing methods were used to measure air leakage rates in these homes.

Whole-House Tightness

A two-point depressurization blower door test (house at −50 Pa and −25 Pa relative to outside) was conducted on each home with supply registers open to the home interior. House tightness results are expressed in standard cubic feet per minute (SCFM).

These homes have an average tightness at 50 Pa (ACH_{50}) of 4.59 ACH, which is very tight by any standard applied to site-built or manufactured homes. The ASHRAE Standard 62 imputes an ACH_{50} of 7.0 ACH, which is the intended MAP performance level. A 1992 study of 131 manufactured homes built to near-MAP specifications found an average ACH_{50} of 6.10 ACH. The impact evaluation of MAP (Baylon et al. 1995) found an average ACH_{50} of 5.50 ACH for a sample of 157 MAP homes.

Effective Ventilation Rate

The effective ventilation rate describes the actual rate at which pollutants are removed from the home by introduction of outside air and removal of stale indoor air. The effective ventilation rate is generally less than the time-weighted average ventilation rate, which is the rate commonly used for heat loss calculations.

The tracer gas decay test was performed by injecting sulfur hexafluoride (SF_6) into the home's air handler until the indoor concentration (measured at a central sampling point) reached about 5 parts per million (ppm) at a central sampling point. The air handler fan was left on, mixing fans were placed in all rooms to circulate the air, and the concentration was allowed to drop by approximately 10%. The air handler fan was then turned off. The gas concentration was allowed to drop by an additional 10%. The house air change rate for both cases was determined from the slope of a linear regression of the natural log of the tracer concentration versus time. Tests were performed during the early morning, with the ΔT between inside and outside usually 20°F or more during the testing period. Gas concentration is measured onsite by a portable infrared photoacoustic spectrometer.

Table 2 shows the results of the decay tests with the air handler fan on and off. With the fan off, the natural ventilation rate ranged from 0.07 ACH to 0.18 ACH, averaging 0.12

Table 2. Air Leakage Summary

	Blower Door		Tracer Decay[3]		
Site ID	Q50[1] [SCFM]	ACH_{50}[2] [vol/hr]	Fan Off	Fan On	Difference
M01	504	4.00	0.10	0.22	0.12
M02	1257	5.17	0.16	0.20	0.04
M03	989	3.20	0.18	0.28	0.10
M04	840	3.40	0.16	0.16	0.00
M05	766	3.25	0.10	0.13	0.03
M06	1050	4.23	0.07	0.13	0.06
M07a/b	1039	5.50	0.10	0.23	0.13
M08	533	5.07	0.12	0.64	0.52
M09	820	7.50	0.11	0.39	0.28
Average	**866**	**4.59**	**0.12**	**0.26**	**0.14**
Std. Dev.	**247**	**1.39**	**0.04**	**0.16**	**0.16**

[1]Total leakage in standard ft^3/min (SCFM) with ducts unsealed, all interior doors open, and house depressurized to 50 Pa. Furnace and exhaust fans off. Measured with Minneapolis Model 3 blower door.
[2]Same conditions as above but leakage expressed in air changes per hour.
[3]Total leakage expressed in air changes per hour based on tracer gas decay test. Tracer tests done with all interior doors open.

ACH. Under these testing conditions of stack-dominated infiltration/exfiltration (which is the norm in much of the Pacific Northwest, since sustained wind-driven infiltration/exfiltration is generally limited), none of the houses meet the ASHRAE Standard 62 recommended minimum effective ventilation rate of 0.35 air changes per hour (ASHRAE 1989).

The difference between fan-on and fan-off house air change rate represents duct leakage and induced infiltration caused by operation of the air handler fan. Depending on the natural infiltration rate and the amount of duct leakage, the amount of induced infiltration can be considerable (Palmiter and Bond 1991). With the furnace running (air handler fan on), the effective ventilation rate increased to an average of 0.26 ACH.

The tracer decay tests are likely to be biased low for purposes of estimating heat loss due to air infiltration/exfiltration, and directly quantifying duct leakage. The first tracer test introduces gas into the belly area through duct leaks, and some of this tracer must remain in the crawl space and belly, only to re-enter the house during the fan-off tests. While this prevents a direct estimate of duct leakage, the behavior of the tracer mimics airborne pollutant behavior, providing a useful estimate of indoor air quality.

These homes are equipped with mechanical ventilation systems (exhaust fans on 24-hour timers). Field measurements generally found the fans delivered airflows adequate to meet Standard 62 if the fans were operated nearly continuously.

Duct Leakage

Table 3 summarizes duct leakage measurements. During this test, supply registers and the furnace cabinet are temporarily sealed and a calibrated fan is used to pressurize the sealed duct system to two reference pressures: 25 Pa and 50 Pa. Duct

Table 3. Duct Air Leakage Summary

Site ID	Total Leakage at 50 Pa [SCFM]	Exterior Leakage at 50 Pa [SCFM]	Exterior Leakage at 50 Pa as a % of total at 50 Pa	Total Leakage at 25 Pa [SCFM]	Exterior Leakage at 25 Pa [SCFM]	Exterior Leakage at 25 Pa as a % of total at 25 Pa
M01	118	51	43	76	36	47
M02	179	126	70	117	86	74
M03	232	122	53	150	96	64
M04	122	34	28	77	24	31
M05	201	105	52	123	67	54
M06	158	82	52	102	54	53
M07a	308	103	33	203	63	31
M07b	279	103	37	185	72	39
M08	234	88	38	157	52	33
M09	191	74	39	122	44	36
Average[1]	**194**	**87**	**45**	**125**	**58**	**47**
Std. Dev.	**60**	**31**	**13**	**40**	**23**	**15**

[1]Site M07b not included in summary statistics. Measured with Minneapolis Duct Blaster.

external leakage is measured similarly, except the home's interior is pressurized in turn to 25 and 50 Pa with the blower door so that the pressure differential between duct system and home interior is reduced to around zero. At this point, any measured duct leakage is assumed to be to outside the home's interior and is classified as "exterior leakage."

The average exterior duct leakage at 50 Pa is 87 SCFM, with a standard deviation of about one-third of the mean. Site M01, with trunk ducts made of fiberglass duct board rather than sheet metal and the smallest double-section home floor area (960 ft^2), and Site M04, with a longitudinal floor, had the lowest duct leakage to outside. The single-section homes have the next smallest exterior leakage. Exterior leakage at 25 Pa averages 58 SCFM. This is a better estimate of actual exterior leakage, since 25 Pa is close to the average static pressure measured in these homes when the furnace is operating normally.

Duct system static pressure is measured so that duct leakage at normal system operating pressure can be calculated. The duct system static pressure is measured with a static pressure tip (usually a compact Pitot tube) inserted into the supply plenum or supply register close to the furnace. Rather than using the measured exterior duct leakage at 25 Pa or 50 Pa, Ecotope uses a reference pressure equal to 80% of the measured system static pressure to represent the average leak driving force when the air handler is running. This 80% factor is based on experience with manufactured home supply ducts, which, because of their shorter runs and lack of traditional supply plenum, generally maintain relatively high static pressures when the air handler operates.

Duct leakage is calculated using the basic volumetric flow equation, $\mathbf{Q} = \mathbf{Cp^n}$, where Q is the flow (leakage), C is found empirically from the two point total duct leakage test (reported in Table 3), and n is assumed to be 0.65 (a common assumption for a flow exponent generally associated with the leaks found in residential building materials and ducts).

Just as blower door results are normalized by house size and expressed in air changes per hour (ACH), duct leakage can be normalized by air handler size and expressed as a percent of the air handler flow (or "supply leakage fraction"). We also do this routinely because the supply leakage fraction is a primary input for a duct system model under development at Ecotope. The last column of Table 4 contains the supply leakage fraction for these homes. The average supply leakage fraction is just under 9%, with the lowest value calculated for Site M04 (2.1%).

EFFICIENCY MEASUREMENT RESULTS

Duct conduction and air leakage are the main contributors to decreased heating efficiency. The alternating coheat test

Table 4. Heating System Flows & Pressures

	Exterior Duct Leakage at 25 Pa [SCFM]	Duct Leakage at 25 Pa per foot of ductwork [SCFM/ft]	Exterior Duct Leakage at 50 Pa [SCFM]	Measured Duct System Static Pressure [Pa]	Reference Duct System Static Pressure[1] [Pa]	Calculated Duct Leakage at Reference Pressure[2] [SCFM]	Sum of Register Flows[3] [SCFM]	Number of Supply Registers	Calculated AH Flow[4] [SCFM]	Supply Leakage Fraction[5] [%]
M01	36	0.41	51	17.0	13.6	23.1	732	7	755.1	3.1
M02	86	0.64	126	21.1	16.9	64.4	715	10	779.4	8.3
M03	96	0.66	122	34.0	27.2	91.8	955	11	1046.8	8.8
M04	24	0.16	34	26.5	21.2	20.5	948	12	968.5	2.1
M05	67	0.47	105	27.0	21.6	60.9	621	10	681.9	8.9
M06	54	0.40	82	25.5	20.4	46.6	600	8	646.6	7.2
M07a	63	0.55	103	13.2	10.6	36.7	917	11	953.7	3.9
M07b	72	0.63	103	16.1	12.9	44.7	888	11	932.7	4.8
M08	52	0.93	88	52.0	41.6	75.2	770	6	845.2	8.9
M09	44	0.85	74	28.2	22.6	42.6	820	7	862.6	4.9
Avg.[6]	**58.0**	**0.56**	**87**	**27.2**	**21.7**	**51.3**	**786**		**838**	**6.2**
Std. Dev.	**23.0**	**0.24**	**31**	**11.2**	**9.0**	**23.8**	**134**		**135**	**2.7**

[1]80% of the measured supply plenum pressure. This is assumed to be the average pressure in the duct system when the air handler fan is on.
[2]Calculated using the reference duct pressure, the flow coefficient calculated from the 25 Pa and 50 Pa total duct leakage tests, and a flow exponent of 0.65.
[3]As measured with either the Lambert FH250 or the Pacific Science Technology Fast-1 Flow Hood.
[4]Sum of register flows plus the calculated duct leakage at the reference pressure.
[5]Calculated duct leakage divided by air handler flow.
[6]Site M07b not included in summary statistics.

measures the combined effect of these losses under typical heating season conditions.

Testing Conditions

Outdoor conditions, combined with house physical characteristics, are the primary determinants of heating system efficiency. To ensure the homes were tested during common Pacific Northwest weather, the thermostat and coheater setpoints were set so that that a temperature difference of at least 30° F was maintained. At one site, the temperature difference was somewhat less than 30° F, so the efficiencies measured at this site are probably optimistic. Table 5 summarizes testing conditions during the alternating coheat tests.

Efficiency Definitions

Two measures of heating efficiency, as defined in Chapter 29 of the 1992 ASHRAE *HVAC Systems and Equipment* volume, are extracted from the real-time data. The first measure is the *cycling heat delivery efficiency*, which is defined as the total useful heat delivered to the supply registers while the *air handler is on*, divided by the power input to the furnace (including air handler fan power). The total useful heat delivered is determined by comparing the rate of energy delivery through supply registers (based on temperature and flow measurements) to the power input to the furnace. This measure of efficiency does not take into account any heat recovered from the ducts, belly region, and floor structural members when the air handler fan is off. Cycling heat deliv-

Table 5. Temperatures During Testing (°F)

Site ID	Avg. Room[1]	Avg. Crawl	Avg. Out[2]	Δ Out[3]	Supply Registers[4]	Δ Supply[5]
M01	75.6	48.2	44.1	31.5	104.2	28.7
M02	76.3	46.6	40.7	35.6	114.9	38.7
M03	74.8	47.5	45.6	29.2	102.6	27.7
M04	74.1	44.1	33.4	40.7	102.4	28.3
M05	75.7	48.4	42.4	33.3	115.1	39.3
M06	74.1	*[6]	48.4	25.7	102.2	28.2
M07a	72.1	49.3	28.9	43.2	102.4	30.3
M07b	72.0	49.6	31.9	40.1	102.6	30.6
M08	72.5	*[6]	33.9	38.6	111.8	39.3
M09	73.8	*[6]	39.5	34.3	101.3	27.5
Average	**74.1**	**47.7**	**38.9**	**35.2**	**105.95**	**31.9**

[1]Average of heating zone control temperatures (6–11 control temperature measurement points per home).
[2]Outside thermocouple shielded from night sky.
[3]Average of heating zone control temperatures minus outside temperature.
[4]Flow-weighted average of register temperatures during furnace cycling.
[5]Average flow-weighted supply temperature minus average inside temperature. When multiplied by the sum of supply register flows, this gives the heat delivered to the home through the supply registers.
[6]Crawl temperature not measured at these sites. These sites had no skirting; therefore, crawl temperature can be assumed to be the outside temperature.

ery efficiency is measured to enable an estimate of the amount of usable heat recovered during furnace off-cycles.

The second measure is *overall system efficiency*. System efficiency is defined as the total useful heat delivered to the conditioned space during the entire period of furnace cycling, divided by the power input to the furnace (including fan power). "Total useful heat" here refers to the electricity that non-ducted electric heaters (such as baseboards) would use to maintain the same average heating zone temperatures as those provided by the furnace during normal cycling. System efficiency is of primary interest because it includes most "real world" effects on heating efficiency: duct conductive loss, duct air leakage, extra infiltration induced by the operation of the air handler, and heat recovered from the ducts, buffer spaces, and structural members during the furnace off-cycle.

The alternating coheat test is conducted with all interior doors open, so any additional differential pressurization which would be created by closing any of these doors is not included in the measurement. The efficiencies measured should thus be viewed as optimistic estimates of cycling and system efficiency.

System efficiency does not depend on any flow measurements and therefore bypasses a significant source of possible error. Ecotope has spent many hours experimenting with the flow hoods used in this research and has determined that flow measurements are sensitive to supply register model, flow hood position, distance of register from air handler and (probably) other factors. In the single-section homes, very high flows in some registers close to the air handler forced the flow hood outside its normal calibration range. Much more work must be done to develop a reliable airflow measurement protocol.

Efficiency Measurement and Analysis Notes

As stated above, the alternating coheat protocol measures temperatures and energy usage during alternating two hour heating periods. The house is unoccupied during the overnight test. The furnace and portable heaters ("coheaters") are operated automatically to maintain the temperature in each heating zone very close to the average temperature measured during the preceding heating period. The furnace cycling rate is controlled with an adjustable deadband so that overshoot and undershoot are significantly damped.

In this report, a "heating zone" is usually any room with a heating register. Larger rooms sometimes have two registers, and coheaters are usually ganged together for simultaneous operation in these zones. Power is measured directly during these alternating periods with true power meters clamped on the electrical mains. Room and supply register temperatures are measured with Type T (copper-constantan) thermocouple wires.

Data analysis is done with an eye to minimizing thermal mass lag effects. Power measurements taken with the clamp-on true power meters cannot always be 100% accurate during the transition periods from coheat to furnace heating modes, due to short-term thermal mass effects. The furnace will stay on longer to heat the duct and underfloor members which cool off somewhat during the coheat period. Conversely, the first part of the coheating energy cycle requires less heating input energy than later parts in the cycle. This is because the furnace has been cycling and has heated up the floor thermal mass, reducing the overall heating load (a combination of the thermal mass load and the load due to the temperature difference between the thermostat setpoint and the outside temperature).

Earlier coheat tests conducted by Ecotope (Olson et al. 1993) measured the effect of sealing registers during coheater operation instead of leaving them open to the home, as is done for these tests. We were not able to discern any systematic difference in average power usage between the two scenarios and therefore have not sealed the registers in any subsequent tests.

Efficiency Results

Measured efficiencies are summarized in Table 6. System efficiency for these homes averages 83%. The median value (excluding test M07b, which was a retest of Site M07a in order to assess the effect of artificially diverting furnace flow away from the cross-over duct entry point) is also 83%.

The last column in the table, the heat recovery fraction, shows the relationship between the cycling heat delivery efficiency and system efficiency. The ratio is not indexed to a common point, so homes with similar cycling heat delivery efficiency and system efficiency (e. g. Site M04) may have a small heat recovery fraction even though their efficiencies are higher than average. A relatively high system efficiency and cycling efficiency indicate limited exterior duct leakage and effective performance of belly insulation. On average, about 40% of the heat apparently lost during furnace operation (to the belly region, to floor structural members, and to other thermal bypasses) is recovered as useful heat during the furnace off-cycle.

The homes with lower system efficiency warrant some mention, since Ecotope was able to identify some possible reasons for their relatively poor performance. Site M05 appeared to have some sort of blockage in the cross-over duct that we could not positively identify, even on a return visit. Register flows on the side of the home containing the furnace (the "A" side) were markedly larger than on the

Table 6. Measured Heating Efficiencies

Site ID	Width Class	Floor Type	System Efficiency[1] [%]	Cycling Heat Delivery Efficiency[2] [%]	Heat Recovery Fraction[3]
M01	Double	Transverse	83	64	0.53
M02	Double	Transverse	89	74	0.58
M03	Triple	Transverse	81	67	0.42
M04	Double	Longitudinal	87	85	0.14
M05	Double	Transverse	74	61	0.34
M06	Double	Transverse	79	71	0.28
M07a	Double	Transverse	78	67	0.34
M07b	Double	Transverse	76	65	0.32
M08	Single	Transverse	86[4]	77	0.39
M09	Single	Transverse	89	76	0.54
Average[5]			**83**	**71**	**0.39**
Median			**83**	**71**	**0.38**
Std. Dev.			**5.3**	**7.5**	**0.15**

[1]System efficiency is the total heat delivered to the conditioned space divided by the energy output of the heating system, as measured by the co-heat method.
[2]This efficiency is the heat delivered to the home though supply registers during the time the air handler fan is running divided by the energy output of the heating system. It does not account for factors such as supply leaks to the conditioned space, heat recovered from ducts during the of-cycle, or heat recovered from buffer zones.
[3](System efficiency-cycling heat delivery efficiency)/(1-cycling heat delivery efficiency).
[4]System efficiency for Site M08 is determined based on the home's measured cycling efficiency and the average heat recovery fraction for allhomes but Site M04 (longitudinal floor). The heat recovery fraction reported for Site M08 is the average for all sites but M04.
[5]Summary statistics do not include Site M07b. Summary statistics for heat recovery fraction also do not include Site M08.

other side of the home (the ''B'' side), which can decrease heat delivery efficiency since the rate of energy delivery through registers decreases as supply flow drops. Ecotope attempted to replicate this condition at Site M07 but was unable to restrict the flow as dramatically as was measured at Site M05. The system efficiency for the second test at site M07 (M07b) was very similar to the first test (M07a).

The single-section homes, Sites M08 and M09, performed relatively well. These units have lower-than-average duct leakage, fewer registers and thus riser takeoff joints than the multi-section homes, and no cross-over duct. There were some problems with the system efficiency data for Site M08, so its system efficiency was derived from the measured cycling efficiency and the average heat recovery fraction for the other homes (excluding Site M04, which has a longitudinal floor). This procedure probably underestimates Site M08's system efficiency somewhat, since the calculation is based mostly on double-section homes with cross-over ducts. However, the calculated system efficiency of 86% is reasonable, given the similarity in floor design, cycling heat delivery efficiency, and testing conditions between Site M08 and M09. (These units were set up side-side on a dealer lot and were tested on successive nights with very similar ambient temperature profiles.)

Site M04 has a longitudinal floor and therefore less separation of ducts from the home's interior and no supply register risers (which reduces duct surface area and therefore reduces conductive losses). Almost all of the energy delivered to the air stream at the furnace finds its way into the conditioned space as useful heat.

Annual Heating Energy Impacts

Table 7 predicts annual cost impacts of varying levels of heating system efficiency in MAP homes. The minimum, maximum, and average system efficiencies reported in Table 6.2 are applied to a 1400 ft² MAP home sited in Portland, OR and Boise, ID. This prototype home was used as the basis for calculating the final cost-effectiveness of MAP (Baylon et al. 1995). The energy use of the prototype home (excluding duct losses) is simulated with *SUNDAY® 3.0* (Palmiter et al. 1987), a program commonly used to estimate heating requirements based on building thermal performance and solar gains. The base heating load for the prototype home, as found by *SUNDAY®*, is divided by average system efficiency to calculate the annual heating energy requirement.

Added yearly costs, calculated with this method, are generally modest for homes insulated to MAP specifications and sited in public utility districts in the Pacific Northwest. This is especially true for a home with above-average system efficiency sited in a relatively mild climate such as Portland (4520 heating degree days, base 65° F, based on 1961–1990 data). A less efficient home sited in a colder climate such as Boise (5871 heating degree days, base 65° F, based on 1961–1990 data) can cost the homeowner considerably more over the course of a heating season: around $100 for the minimum efficiency case. As the home ages and duct air sealing products fail, annual costs of duct inefficiency will increase. Costs will also be higher in private utility service territories and in more severe climates.

SUMMARY OF FINDINGS

This report presents the results of field measurements conducted on nine electrically-heated manufactured homes built to Model Conservation energy-efficiency standards and sited

Table 7. Annual Heating Energy and Cost Adders

	Measured System Efficiency	Annual increase in Portland heating energy (kWh)	Annual increase in Portland cost	Annual increase in Boise heating energy (kWh)	Annual increase in Boise cost
Average	83%	773	$39	1161	$ 58
Minimum	74%	1326	$66	1991	$100
Maximum	89%	466	$ 23	700	$ 35

Assumptions

1400 ft² prototype home is built to MAP specs (U_o = 0.0532 Btu/hr °F ft²).

Glazing percentage is 12% of heated floor area (168 ft²)

Combined (natural + mechanical) infiltration rate of Portland home is 0.24 ACH; combined infiltration rate for Boise home is 0.29 ACH (based on Baylon et al. (1995) and location of homes).

The resulting UA of the Portland home is 261.3 Btu/hr °F; the UA of the Boise home is 270.9 Btu/hr °F

Thermostat is set to 67° F throughout the heating season with no setback.

Internal gains are set to 2500 Btu/hr.

Solar multiplier is set to 0.45 (combination of low-ε coating on windows and intentional shading devices) and window area.

System efficiencies are assumed to be typical for the heating season and are applied to the base heating load to estimate added energy requirements.

Electricity cost is $0.05/kWh.

in the Pacific Northwest. The primary purpose of the research was to estimate the effects of forced-air heating distribution systems on heating energy requirements under typical winter conditions. The research was not conducted on a large enough sample to draw definitive conclusions; however, it is an important preliminary effort towards understanding the operation of forced-air systems in new manufactured homes.

The average and median system efficiency as defined by ASHRAE (1992), including heat recovered from buffer spaces and bypasses, is 83% for these homes. This means that manufactured homes built with high levels of underfloor insulation (R-33), duct insulation, and displaying limited duct leakage, use on average 1.20 times as much heating energy as they would if heated with zonal electric baseboard heaters.

Average system efficiency measured for these homes is considerably better than that found during a study of 24 Pacific Northwest site-built homes tested with a very similar protocol during the 1992 and 1993 heating seasons (Olson et al. 1993). That study found an average system efficiency of 71% for the 22 homes which had at least half of the ductwork located outside of the thermal envelope. The site-built homes had ducted return systems and much longer and leakier supply systems than the manufactured homes in this study. Even though the manufactured homes in this study have furnaces located inside the home's thermal envelope, losses associated with the forced-air heating system add appreciably to the annual heating energy requirement.

These homes have limited air leakage, with an average ACH_{50} of 4.59. Tracer gas measurements found an average effective natural ventilation rate of less than one-third of that recommended by ASHRAE Standard 62. The mechanical ventilation systems installed in these homes deserve more study, given the relatively low natural infiltration/ventilation rate of these homes.

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