An Analysis of Air Distribution System Losses in Contemporary HUD-Code Manufactured Homes

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Manufactured homes, often referred to as HUD-code homes, are continuing to grow in importance as a national housing resource and represented 23% of all new home construction in 1995. In spite of groundbreaking work to characterize the performance of air distribution systems in site-built housing, in new manufactured homes, the subject has been largely ignored. Field data was gathered from 24 typical new HUD-code homes in four regions in the continental United States. This study describes air distribution system losses estimated through an analysis of system and distribution efficiencies. The results presented include summaries of the physical audits, air tightness testing, and separate air distribution system analyses for the heating and cooling climates. Losses attributable to air distribution systems range from 18%–40%. An example of the operating cost penalties of air distribution system losses is described. Opportunities for improvement in air distribution system performance over current manufactured housing practice are discussed. This paper is a synopsis of the research study ''Air of Importance: A Study of Air Distribution Systems in Manufactured Homes.''

INTRODUCTION

Manufactured homes are continuing to break barriers of both acceptance and of market share and are growing in importance as a national housing resource. The industry grew 13% in 1995, despite increased manufacturing costs resulting from enhanced construction requirements mandated by the U.S. Department of Housing and Urban Development (HUD) in October 1994. Manufactured homes represented 23% of all new home construction in 1995—a total of 340,000 homes, which is an increase of 100% over 1991 production levels.

The subject of air distribution in buildings is relatively poorly understood, and in manufactured homes the topic has been nearly ignored altogether. Studies that do exist focus primarily on older homes that do not reflect current construction practices. These studies and other anecdotal data suggest that energy losses attributed to poor air distribution performance in manufactured homes may be similar in magnitude to the losses reported for site-built homes. However, due to the different construction techniques used in manufactured homes, the sources of and solutions to these air distribution problems may be unique from those found in site-built homes.

Background

The design of air-distribution systems in manufactured housing is driven by different factors than in site-built homes. Since high production volumes are needed to produce these homes economically, systems that require more expertise to install, that might slow production, or that are expensive, are avoided. The entire operation of fabricating and installing the duct system in a manufactured housing plant is measured in minutes, rather than in hours as is typical for a site-built home. The total cost of materials and labor for a manufactured home duct system is generally only a few hundred dollars per home. This extremely low-cost baseline represents a formidable design constraint in the pursuit of more energy-efficient alternatives to current manufactured housing air-distribution system practice.

The Federal Manufactured Home Construction and Safety Standards (FMHCSS) provides the manufactured housing industry with a exemption from state housing codes. However, the standards do prescribe design criteria that affect building and air distribution performance. The physical area available for manufactured homes' air distribution systems is also limited by federal interstate transportation height regulations which implicitly restrict manufactured housing air distribution design. Within these constraints, however, a standard method of duct construction has evolved that, due to its ease of fabrication, short installation time, and low cost is used in virtually all manufactured home plants across the country.

Manufactured housing ducts are typically fabricated in the plant by equipment that transforms coiled sheets of aluminum into rectangular duct of a uniform cross-section. This duct is used as the supply trunk and may measure as long as 65 feet. Duct caps are typically screwed onto the ends of the trunk and are sealed with tape, then the trunk is placed between the floor insulation and the floor joists. Supply registers are mounted perpendicularly to this trunk with short duct boots made from similar material that are secured by tabs that are folded inside the trunk and covered with tape.

Occasional variations to this design include overhead ducting, graduated or tapered duct trunk (usually made of fiberglass board), and branch ducts used to satisfy registers located at the perimeter of the home. Multi-sectional homes also employ an external duct (almost always flexible), referred to as the crossover duct, to connect the supply duct trunks in each section. Air return is assured by door undercuts and through-the-wall transfer grilles that create a path through the building space back to the return grille, which is directly connected to the air handler.

Scope

The objective of this study was to characterize the performance of air distribution systems in manufactured homes built to the requirements of the new FMHCSS, and to propose appropriate energy-efficient alternatives to current practice. Computer analyses were used to model operating costs from short term duct performance, building shell characteristics and climate data. An effort was made to identify the source of the air-distribution system losses in order for future attention to be focused on the most significant losses.

Because the performance of air distribution systems varies with climate, testing was conducted for appropriate regions in the continental United States. The manufactured housing standards delineate three different thermal design zones, as shown on Figure 1. Although there is a considerable range of space-conditioning loads within each of these regions, the FMHCSS permits homes sited in each of these regions to meet a single thermal efficiency value. The minimum thermal shell requirements are expressed as a maximum heat loss transmission coefficient (U_o) of 0.116, 0.096, and 0.079 Btu/(hr (F ft^2) for homes sited in HUD zones I, II, and III respectively. Although the design criteria mandated for the air-distribution systems is identical for each of these zones, the differences in the shell insulation levels will have an indirect influence on air distribution system performance.

In addition to the three HUD zones, the state of Florida and the Bonneville Power Administration (BPA) region have significant local variations in manufactured housing air distribution system design which warrant their being tested separately. Florida manufactured homes almost exclusively employ overhead supply ducting systems, and the cooling equipment, including the air handler, is located outside as packaged systems. This configuration is a design rarely found elsewhere in manufactured housing. Homes in the BPA region were built to the Manufactured Housing Acquisition Program (MAP) standards. The MAP standards far exceed those specified by HUD, (the maximum U_o for MAP homes is 0.053 Btu/(hr (F ft^2)), and include specific measures to increase air-distribution performance. The MAP homes are considered the upper limit of practical energy efficiency, given current manufactured housing construction practices. Existing data from MAP home air distribution analyses are used as a benchmark for this study.

Field data was collected from 6 homes in New York, 8 in North Carolina, 5 in Alabama, and 5 in Florida. Twenty of the study homes were multi-section, four were single-section. Other significant regional differences were also taken into account. New York homes are primarily heating climate dominated and are heated with fossil fuels, while the Florida homes are primarily cooling climate dominated. The North Carolina and Alabama areas have a mixed heating and cooling climate.

METHODOLOGY

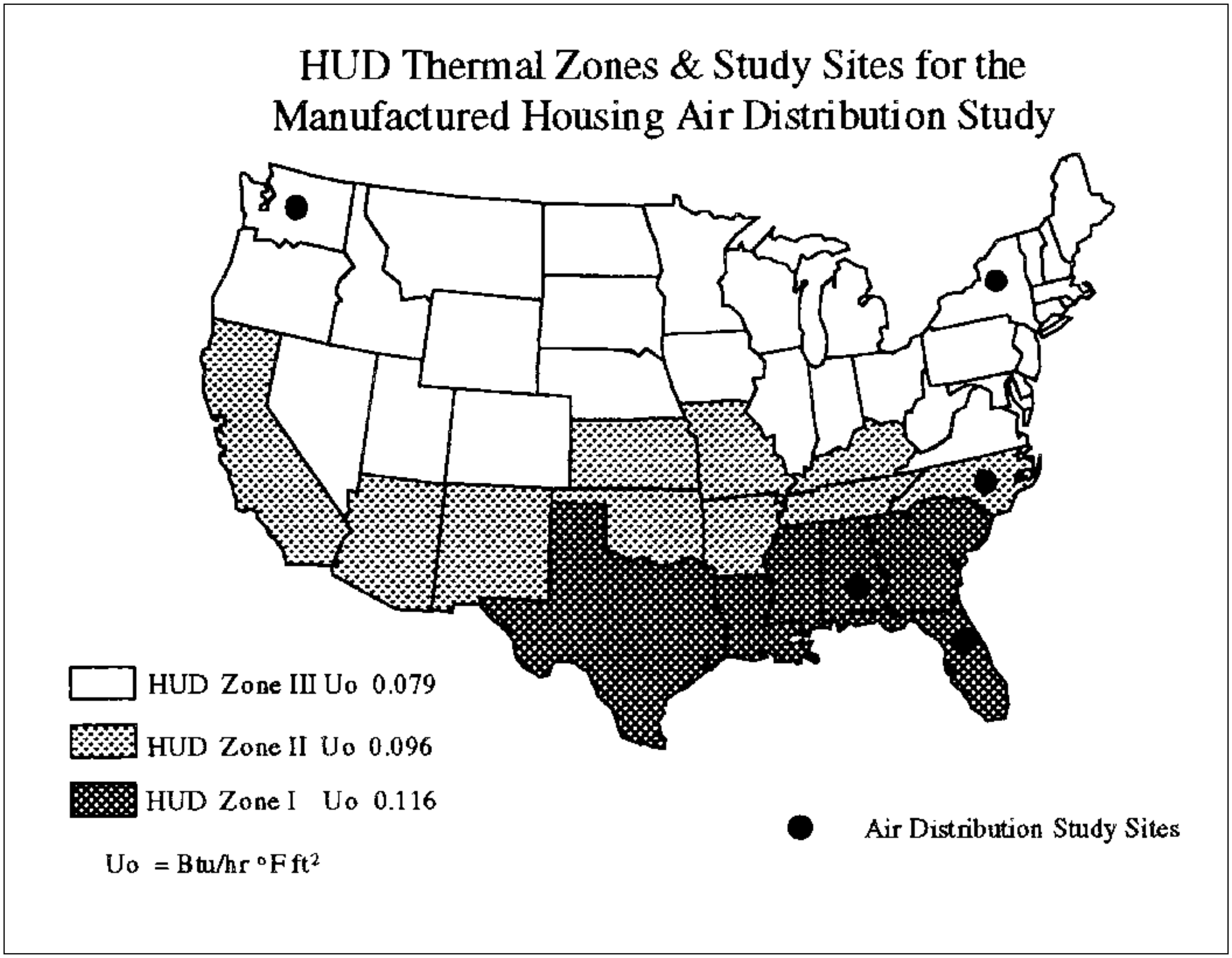
A data-gathering protocol for all of the field work was developed which combined a physical audit of the homes, pressure diagnostics, tracer gas tests, and measurements of the shell and duct leakage. No attempt was made to randomly select the study homes, though an effort was made to include a variety of different manufacturers in the sample. The data collected in the field also included short-term temperature and humidity monitoring of the home, duct zones, and ambient conditions during prescribed space conditioning operation.

The air distribution system performance was arrived at separately for the heating and cooling climates using different approaches. The heating analysis was conducted for the New York and North Carolina homes by Ecotope Inc., and specifics of their analysis are contained in a more detailed report. Field data collected during heating operation played a large part in the construction of an empirical efficiency model for the heating climate analysis. The cooling climate analysis for the Florida and Alabama homes was conducted by the Florida Solar Energy Center. With less detailed cooling system efficiency data available for support, the approach used for the cooling analysis placed more reliance on an energy simulation program that directly modeled distribution efficiency during cooling conditions.

Heating Analysis

The heat delivery efficiency is defined as the ratio of the thermal energy supplied through the registers of the distribution system while the fan is on, to the thermal input to the ducts from the furnace. Within certain limitations, this can be measured directly. The steady-state heat delivery efficiency was obtained by measuring air flows and temperatures at the duct registers and energy input to the furnace. Air handler flow was calculated by adding the sum of the supply register flows to the exterior duct leakage calculated for the measured duct pressure. The supply leakage fraction, also

Figure 1. HUD Thermal Zones & Study Sites for the Manufactured Housing Air Distribution Study



used in the analysis, was calculated by dividing the computed exterior duct leakage by the air handler flow.

System efficiency is defined as the ratio of the total energy delivered to the conditioned space divided by the total energy input to the furnace. Thus system efficiency incorporates off-cycle losses and heat recovery back into the home. An estimate of system efficiency was derived from data collected during this study and from other data borrowed from previous coheating tests of MAP homes. In coheating tests, a home is alternately heated with the furnace and then with an array of small electric resistance heaters while being kept at essentially the same temperature. The ratio between the average power in the two heating modes is a direct measure of system efficiency. With information collected during the MAP home coheat study, estimates were made for off-cycle losses and heat recovery. These factors were borrowed from the MAP coheat study to estimate system efficiency for the HUD-code homes. The method is beyond the scope of this report, but can be found in the report cited earlier on the heating analysis.

Since the MAP homes have more underfloor insulation and less duct leakage than the HUD-code homes, the amount of heat recovered during off-cycles is probably higher in the MAP homes. Therefore, since the factors that are used to convert steady state delivery efficiency to system efficiency are borrowed from the MAP studies, the reported system efficiency for the HUD-code homes should be viewed as an optimistic estimate.

A mathematical model initially developed by Larry Palmiter of Ecotope, Inc. was used to calculate the relative size of the conduction and convection losses. This model explicitly accounts for the interaction between the energy delivered by the equipment, the air leakage, and the conductive losses in the duct. The mechanically induced infiltration component was calculated separately.

Cooling Analysis

For the cooling analysis, an in-house simulation tool, FSEC 3.0, was used to estimate the air distribution system losses. Mathematical models of the homes studied were constructed from the air-flow testing, and from the envelope, HVAC, and distribution system characteristics observed in the field. Each of the individual elements that contribute to the penalties associated with the incorporation of the air-distribution was modeled. An hour-by-hour energy analysis was performed for each home using typical weather data for the entire cooling season to obtain ''base case'' results. The simulation was repeated with the duct leakage and duct conduction input terms entered as very small values. The ratio of the energy use predicted for this minimum configuration to the energy use predicted for the base case configuration is calculated as the distribution efficiency. The distribution system losses by components was then constructed from the summation of all the appropriate energy flows modeled in the analysis.

RESULTS

The results presented are divided into four sections. First are the results of the physical audit and testing and then the heating analysis and the cooling analysis are presented. Because the heating and cooling analyses were approached differently, no attempt is made to compare these results side-by-side. Finally, an example of the operating costs of the air distribution system losses is given.

Physical Audit and Testing of the Sample Homes

The sample homes were typically newly constructed double-section homes. The MAP and Alabama homes were not new; however, these homes were selected because they met the new HUD-code standards and because useful data existed from recent studies. A few single-section homes were included in the sample. The average floor area for the homes was 1440 square feet (see Table 1). In general, all of the homes were built consistent with the HUD-code thermal shell requirements except for the North Carolina zone II homes. In most cases these homes surpassed the zone II requirements and were built to meet zone III requirements.

The blower door test for shell tightness shows that this sample of the HUD-code homes is relatively leaky at about 1.5 CFM50 per square foot of floor area. Leakage over 1.0 CFM50 per square foot of floor area is generally considered to be excessive in site-built homes. The Florida homes were relatively tight, with a leakage rate of 1.1 CFM50 per square foot of floor area. However, this is still unremarkable compared to the leakage rate reported from the study of MAP homes of 0.56 CFM50 per square foot of floor area.

The results are similar for the duct leakage tests made with a duct blower (a small calibrated fan designed for duct pressurization tests). Duct leakage to the exterior in the HUD-code homes was 0.08-0.10 CFM25 per square foot of floor area, compared to 0.03 CFM25 per square foot of floor area for the MAP homes. Exterior duct leakage above 0.03 CFM25 per square foot of the floor area is typical, but considered leaky. The Florida home leakage data included one significantly leaky system which, when removed from the sample, changed the Florida homes' duct leakage rate to 0.04 CFM25 per square foot of the floor area. The overhead ducts in the Florida homes were often sealed with adhesive foam. This product is used in the building envelope system to adhere the attic trusses to ceiling panels and, with the ducts in the ceiling cavity, makes for a convenient and near air-tight duct sealer. In spite of the relatively tight ducts, tracer gas tests showed the Florida homes to have the largest differential in air changes per hour during air handler operation. This may be due to the fact that only in Florida are the air handler blowers located outside the thermal envelope. The blower cabinet is the site of the largest driving pressures in the duct system, and this high pressure may be forcing a disproportionate amount of air to the outside relative to the total area of leaks it contains.

Some obvious shortcomings were observed in the duct systems. Often, the protective polyethylene sheathing making up the outside air barrier for the floor system was torn, exposing the ducts to the outside. For example, tears in the air barrier measured in the 8 North Carolina homes averaged 3.2 square feet. During duct tightness testing, air could be felt flowing from these tears. A well sealed air barrier acts to redirect air leaked from the ducts back into the building and will also minimize the ducts' exposure to outside temperatures. Pressures were measured in each floor cavity near the ducts during the blower door tests. The average pressure in the cavity with reference to the inside in the North Carolina homes was found to be 29 Pascals when the house was depressurized at 50 Pascals. If the air barrier were sealed, this pressure would be zero. These floor cavities communicate more easily with the outdoors than the indoors, resulting in air leaked from the ducts being lost to the outside, and thin-walled metal ducts exposed directly to outside temperatures.

The metal tape used in the factory for sealing duct boots to the trunk was observed to be failing, even after being in service only two months. This was particularly evident near the furnace outlet, where high temperatures may have a detrimental effect on tape durability. Lastly, the cut-outs in the duct trunk were often observed to be roughly cut, and the duct boots often did not make complete contact with the

Table 1. Average Physical Characteristics and Leakage Testing Results

	Sample Size (section)[a]	Average Area (sq. ft.)	Average Volume (cu. ft.)	Blower Door Test CFM50	Blower Door Test ACH50	Tracer Gas Δ ach on/off	Duct Blower CFM25 Exterior	Supply Leakage Fraction %
BPA/MAP HUD zone III	8 (7m/1s)	1506	11295	847	4.5	NA	48	5.9
New York HUD zone III	6 (4m/2s)	1433	11436	2274	12.0	0.09	148	11.3
North Carolina HUD zone II	8 (8m/0s)	1601	12905	2098	10.2	0.13	188	14.5
Alabama HUD zone I	5 (3m/2s)	1422	11201	2132	11.0	0.21	108	10.8
Florida HUD zone I	5 (5m/0s)	1236	9784	1381	8.6	0.30	102	10.0

[a] Section refers to m = multi-section, or s = single-section homes. The project aimed to use as many multi-section homes as possible.

trunk, resulting in visible leak sites in the duct boot to trunk connections.

Three homes in North Carolina were revisited six months after the original tests. Additional degradation was found including more tape failure and additional tears into the belly material from post set-up activities. Duct leakage to the exterior in these homes had increased by an average of 35%.

Heating Results

The delivery efficiencies and the system efficiencies analyzed for the heating analysis are illustrated in the first portion of Table 2. The analysis of the MAP homes is similar and is therefore presented alongside for comparison. The empirically-derived, steady-state heat delivery efficiency averaged 64% for the HUD-code zone II and zone III homes. The system efficiencies derived from these values averaged 55%.

The air distribution system losses by source are illustrated in Table 3. These results were better correlated by how the ducts were installed, rather than where the homes were located. Ducts are typically installed on top of R-22 underfloor insulation. However, some of the ducts were also covered on top with R-7 fiberglass insulation. The main difference in the results is that the uncovered ducts lost an additional 17% of energy due to conduction losses over that lost

Table 2. Efficiency Results

	Steady-State Delivery Efficiency	System Efficiency	Distribution Efficiency
Heating:			
BPA/MAP HUD zone III	83%	85%	
New York HUD zone III	64%	53%	
North Carolina HUD zone II	63%	56%	
Cooling:			
Alabama HUD zone I			88%
Florida HUD zone I			73%

Table 3. *Estimates of Distribution System Losses by Source: Heating Protocol*

	MAP Homes (%)	HUD-Code Homes (%)	
		Insulated Ducts (R-7)	Uninsulated Ducts
Conduction	7	10	27
Air Leakage	6	18	20
Increased House Infiltration	2	4	4
Sum of Losses	15	32	51
System Efficiency	85	68	49

Note: These values are based on a 1400 square foot home with an electric heating system, an 850 cfm blower, 120 ft of ductwork, and a supply leak fraction of 10% in HUD-code, and 5% in MAP homes.

by the ducts completely wrapped with insulation. The current trend in manufacturing these homes is to wrap the ducts with insulation, and the results for the completely covered ducts are perhaps a better indication of current practice.

Cooling Results

The focus of the cooling analysis was the modeling of the distribution efficiencies from the physical air distribution system characteristics. These values average 81% as seen in the second portion of Table 2. The different analytical approaches employed makes any direct comparison of the heating and cooling analyses invalid; furthermore, system efficiency and distribution efficiency are not the same. Some discrepancy was anticipated simply due to the different approaches employed. However, a higher air distribution system performance is expected for cooling climates where the thermal driving forces are generally less severe.

The analysis of the losses by source show that the homes built with overhead ducts differ significantly from the floor-based duct systems. The cooling simulation indicates that losses from overhead duct systems are not as easily recovered as losses from duct systems located in the floor cavity. When air leaks into the floor cavity of a manufactured home with floor-based ducts, a significant amount of that cooled air is redirected back into the house and is regained. The FSEC 3.0 model indicates that, when the ducts are mounted in the ceiling cavity, rather than regaining leaked cooled air, hot attic air is instead being sucked into the home through passages in the ceiling plane to replace the air lost due to distribution system leakage. Fifteen percent of the losses were recovered from the floor-mounted ducts, while less than 1% were recovered from the overhead ducts.

Cost Analysis Example

Because of the small sample of homes and the different analytical approaches applied in this study, operating costs for each of the regions are not presented. Instead, one example of the operating costs is illustrated for a home with an area of 1400 ft^2, with 10% glazing area, a natural infiltration rate of 0.35 ach, a 65 °F temperature setpoint, an electric resistance furnace, electricity cost of $0.075/kWh, and Raleigh, N.C., weather. The costs related to heating air distribution system losses only were estimated to be $414. This cost represents a significant opportunity for improvement.

CONCLUSIONS

Success of the MAP approach demonstrates that current designs are capable of effectively delivering heated and

Table 4. *Estimates of Distribution Efficiency Losses by Source Cooling Protocol*

	HUD-Code Homes (%)	
	Underfloor Ducts	Overhead Ducts
Conduction	10.8	9.8
Air Leakage	12.4	11.5
Increased House Infiltration	4.5	5.0
Sum of Losses	27.6	26.3
Regained[a]	15.6	0.7
Distribution Efficiency	88	73

[a] In this analysis, the energy regained through different mechanisms is not credited to individual loss sources. The regained energy is included in the distribution efficiency value.

cooled air to the living spaces of manufactured homes. However, conventional manufacturing, installation and set-up practices in the typical HUD-code homes appear to result in a dramatic degradation in air distribution performance. This is particularly evident during the heating season. Losses attributable to the air distribution systems are, on average, similar in magnitude to those found in site-built homes, and a similar investment to decrease these losses is warranted in the growing manufactured housing industry.

Conduction losses from all of the duct designs investigated are high. Ducts inside the floor cavity suffer from failure of the air barrier to perform as such, especially over time. The crossover duct is typically under-insulated and also poorly connected. Ducts in the attic are subjected to extreme conductive driving forces with little room for more insulation. The effect of tears in the air barrier and sealing the air barrier on the edge should be examined. Packaged air conditioners should have the cabinets well sealed. Ducts need to be sealed and tested in the plant, and a more durable material than the tape used to ‘‘seal’’ ducts needs to be used.

This research is an important first step in describing the efficiency of heating systems in manufactured homes built to the HUD-code. The number of homes studied is still very modest, and some of the techniques are described as experimental at best. However, the efficiency analysis provides a reasonable estimate of energy losses and possible savings from design changes. This is an industry that has demonstrated its ability to change quickly to market and regulatory demands. Already, manufactured housing plants outside the BPA region are experimenting with performance-tested mastic-based duct sealing.

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REFERENCES

Levy, E., F. Conlin, B. Davis, and J. Tyson. 1996. *Air of Importance, A Study of Air Distribution Systems in Manufactured Homes.* Research Triangle Park. North Carolina Alternative Energy Corporation.

Federal Register. 1993. *Manufactured Home Construction and Safety Standards.* Volume 58, No. 204, Rules and Regulations: 24 CFR Part 3280. October 25.

Baylon, D. and B. Davis. 1993. *Cost-Effectiveness of the Manufactured Housing Acquisition Program (MAP).* Ecotope Inc. Seattle. Prepared for Bonneville Power Administration.

Davis, B. 1995. Results of Testing on Homes Built to 1994 HUD Thermal Standards. Seattle. Ecotope, Inc.

Tyson, J., M. Anello, S. Chandra, L. Gu, and M. Swami. 1996. *Manufactured Housing Air Distribution Systems: Field Data and Analysis for the Southeast, Final Report*. Cocoa. Florida Solar Energy Center.

Davis, B., L. Palmiter, and J. Siegel. 1994. *Field Measurements of the Heating Efficiency of Electric Forced Air Furnaces in Six Manufactured Homes*. Bonneville Power Administration.

Palmiter, L. and P. Francisco. 1995. A Practical Method for Estimation the Thermal Efficiency of Residential Forced-Air Distribution Systems. Preliminary results presented at June 1995 ASHRAE symposium on ducts, San Diego, Calif.

Florida Solar Energy Center. 1992. *FSEC 3.0: Florida Software for Enervironmental Computation*. Version 3.0. Cape Canaveral.