Air of Importance

A Study of Air Distribution Systems in Manufactured Homes

A research project sponsored by:

Alternative Energy Corporation
Carolina Power & Light Company
New York State Energy Research and Development Authority
U.S. Department of Housing and Urban Development

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Final report printed May 1996
by Alternative Energy Corporation

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An independent nonprofit organization, Alternative Energy Corporation (AEC) was established in 1980 by the N.C. Utilities Commission in cooperation with the state's major electric utilities to promote energy efficiency. AEC develops, tests, and delivers energy innovations and efficiencies for member electric utilities and their customers. Member utilities are Carolina Electric Cooperatives, Carolina Power & Light Company, Duke Power Company, Nantahala Power & Light Company, and North Carolina Power.

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Acknowledgments

There are many people who deserve thanks for their hard work on this project. I would like to thank Diana Woolley, without whom this project would still be an idea. I would like to thank Emanuel Levy for his constancy and his willingness to coordinate the technical work of others. I would also like to thank AEC and its Board of Directors for allowing me to focus on this project. The Technical Design Committee: Ed Salisbury, Dennis Jones, J.T. Williams, Allen Zimmerman, Bruce Davis, and Mark Modera, helped us keep the project on-target, practical and useful. Many retailers in North Carolina, Florida and New York and their state associations helped us find homeowners willing to participate in the study, and many home owners repeatedly allowed us into their homes for the testing. All of you deserve my heartfelt appreciation. Thanks to Jerry Bruner and the Fleetwood Plant in Roxboro, NC, who, because of their proximity, I used to educate many contractors about manufactured homes. Thanks to NCMHI and Stacey Cheathum who always answered my questions. A special thanks goes to Bob Davis of Ecotope Inc., who does take manufactured housing seriously. And, of course, this project would not have been possible without the support of our partners: Bill Freeborne of the United States Department of Housing and Urban Development, Bob Carver from the New York State Energy Research and Development Authority, and Russell Duncan from Carolina Power & Light Company.

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Foreword

One has only to look at the statistics to see how important it is to consider manufactured housing in any residential energy research. Twenty percent of existing single-family homes in the United States are manufactured, and 25 percent of new single-family homes built last year were factory-built. In North Carolina, the leading state for manufactured-home shipments, 40 percent of new homes last year were manufactured. Sponsored residential energy research has advanced the understanding of building systems in general, but this research is not always transferable from site-built to factory-built housing. The scarcity of articles in the literature dealing with new manufactured homes demonstrates the disproportionate level of research investment being spent in this burgeoning home construction approach. The small amount of manufactured housing research that does exist has recently focused mainly on ways to improve the thermal envelope. This led, in part, to an increase in the thermal requirements for manufactured homes in the recent changes to the HUD Standards (October, 1994).

In the last several years, building scientists across the country have been quantifying the contribution made by air distribution systems to building efficiency loss in site-built homes. Estimates vary, but the average duct system appears to reduce overall system efficiency by 20 to 40 percent. This efficiency loss can have a multiplying effect with air-flow sensitive, compressor-based space conditioning systems such as air conditioners and heat pumps. Meanwhile, air distribution systems in new manufactured homes have received very little attention. This study is a step forward in trying to better understand air distribution in manufactured homes and their affect on overall system performance.

An incentive for the manufactured housing industry to volunteer to improve the quality of their product is found within the home buying market. The industry has demonstrated its willingness to invest in change if such a change improves ability to sell homes or decreases problems that require on-site visits from the retailer or factory to remedy. An in-house survey of 50 manufacturers and 50 retailers showed that a callback cost of 10% was budgeted by the average retailer, and 12% of field visits had to do with a variety of air distribution related issues. A goal of this project was to suggest changes in the air distribution system that will significantly affect these costs. Four technical bulletins were developed as part of this project to help educate retailers, manufacturers, and contractors about how to optimize air distribution performance and at the same time reduce callback expenses for their housing product.

This study analyzed the performance of air distribution systems in 24 manufactured homes in Alabama, Florida, New York, and North Carolina, and compared them with the results of 9 homes built to the more stringent MAP specifications and tested previously in the state of Washington. One of the objectives in this study was to go beyond just describing the magnitude of air distribution system loss and to uncover the source. Understanding the root cause of air distribution system efficiency loss will help to identify the appropriate remedies.

The manufactured housing industry has shown a increasing level of proactivity. For example, by the time the new HUD regulations went into effect in October 1994, many manufacturers were already providing as a standard or, at least as an option, homes with an equivalent level of thermal insulation. The information in this report should help those innovators in the industry improve the quality of their products. It is those in the industry who are proactive and who treat their homes with building science in mind that I hope will benefit most from this report.

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1. Executive Summary

1.1. Introduction

Most research relating to the energy use in manufactured housing has dealt with the performance of thermal envelope, space heating and cooling equipment, and more recently, issues such as whole house ventilation and infiltration. While some studies have looked at energy losses due to air distribution systems (ADS), this area is too often treated as a footnote to the overall performance of the mechanical system.

There are several reasons why this situation has developed. First, energy use associated with distribution systems is generally gauged solely by engineering analyses whose results are based on outdated or unsubstantiated assumptions. Manual J, for example, suggests that duct losses should be assumed to degrade performance by between zero and 15 percent, the latter figure being suggested for ducts placed outside the building's thermal envelope in very cold climates. Recent studies in the site-built area, and now this effort, shed some light on the true performance of distribution systems and suggest that these analysis tools are not particularly accurate predictors of actual system performance.

Second, even with better predictive tools, the quality of installation too often leaves much to be desired. Manufactured homes are erected in a plant under the watchful eye of a quality control supervisor. The critical crossover duct connection is done in the field by contractors operating in a far less regulated environment and not subject to the same rigorous third-party inspections.

Third, exclusive of the manufacturers, there are only a few industry groups with vested interests in distribution systems and fewer advocates with the resources to conduct meaningful research. With the significant improvements in thermal envelope and equipment performance, distribution systems have quickly become one of the critically weak links in making further energy-efficiency improvements.

With these points in mind, this study was designed to make inroads into our understanding of ADS in manufactured homes. The following questions helped shape the design of the project:

- How large are the distribution losses in single- and multi-section homes and what are the principal variants -- in the areas of design, construction, materials, installation -- that influence the magnitude of these losses?

- What practical and economical steps can be taken to mitigate distribution system losses?

- How much energy can be saved by such measures? What are the cost/benefits of and technical/implementation barriers to these measures?

- What kinds of new materials, products, and/or technologies are needed in order to significantly improve distribution system energy performance?

As part of the first phase of this effort, a literature search was conducted that noted a dearth of duct distribution studies generally, and specifically a near absence of research dealing with the performance of thermal distribution systems in manufactured housing (see Section 5). Several citations suggested that thermal distribution system inefficiencies may degrade overall energy performance by anywhere from 15 to 40 percent. These figures are, for the most part, derived from field monitoring of site-built homes. Even in these cases, however, there is no general agreement on the conditions that cause a significant reduction in system efficiency, the steps to take to improve performance, and the impact that changes in construction practice have on the efficiency of the thermal distribution system.

System performance characteristics also appear to vary by climate, as a result of the types of materials used in fabricating the system, and as a function of system location (floor or attic) and layout. In short, there exists an acute gap in our basic understanding of the performance of thermal distribution systems that has two components: (1) how large an impact thermal distribution systems have on energy use in manufactured homes; and (2) the specific conditions that influence when the losses occur. The need to measure the performance of ADS through the field testing of homes was underscored by a group of industry experts serving as advisors to the work. [1]

1.2. Research goals, approach, and study limitations

The study aimed to contribute to an understanding of the performance of air distribution systems (ADS) in manufactured homes through field tests of actual, in situ operation. This poses a challenge for several reasons including the following: field tests are conducted over a short time span and simulation tools are needed to extrapolate the results to entire heating and cooling seasons; and, since system efficiency fluctuates by season, the construction of the home *and* its site location will influence the overall operating efficiency of the ADS. Relatively large performance variations from year to year and from home to home are to be expected. The results of these investigations are displayed throughout the study in precise terms often depicted by graphic representations of ADS performance. The reader should be circumspect in reviewing this material and recognize the limits of the study which include the following:

- Tools available for simulating ADS performance are relatively new and have not been subject to broad use and validation by the engineering community.
- Predicting ADS performance is complex and requires estimating several types of heat and air flow that change over time and may be occurring simultaneously.

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[1] The project was monitored by a team of experts in the area of manufactured housing and/or air distribution systems. The team consisted of the following people: Ed Salisbury of Fleetwood Enterprises, Mark Modera of Lawrence Berkeley Laboratory, Alan Zimmerman of Evcon Industries, Dennis Jones of R-Anell Homes, J. T. Williams of Azalea Mobile Homes.

- Changes in the living environment, such as elevated humidity levels or system imbalances that cause cold spots, were not considered as part of this study. These factors impact overall system performance.
- The sample size is extremely small (33 homes [2]), limiting our ability to generalize from the results.

Despite these limitations, this study suggests that using an ADS degrades energy performance dramatically, mainly as a result of poor installation and set up practices. In the heating mode, the average efficiency reduction was 40 percent (that is, for every 100 BTUs of heating energy entering the ADS, 60 arrived in the living spaces) and in cooling the loss was about 18 percent on average.

In most continental US climates, annual energy use is split between heating and cooling. The efficiency of the ADS as a conditioned air delivery method varies by season, and it is the net impact on energy use that is of ultimate interest in characterizing such systems. However, combining heating and cooling performance is a challenge beyond the scope of this modest effort.

An ADS design that performs fairly well in the cooling months may not be nearly as effective in the heating season and, therefore, tools used to measure performance in the two seasons differ in many respects. In addition, some climatic and design factors, such as relative humidity, are important in measuring performance in one season (cooling in this example) and not the other season. While a leaky duct system is leaky all year round, its impact on total annual energy use and operating efficiency depends on climate and other site factors and often where exactly the leaks occur.

Adding to the list of variables that influence seasonal performance is the placement of the ADS. In most homes, the ADS is primarily located in the interstitial space below the floor, referred to as the belly area. In Florida, however, the practice is to deliver conditioned air to the living spaces from above through attic-mounted ducts. Consequently, the research applied different analytical methods to predict heating and cooling seasonal performance of the ADS and, as a result, there are some differences in the data collection protocols. This is reflected in the structure of the report which is divided into heating and cooling chapters.

1.3. Summary of the performance of ADS in the heating mode

Estimates of ADS performance in the heating mode are based on the results of field tests of 23 homes in three climatically distinct locations. Thirteen of the homes were monitored expressly for this effort (six in New York state and eight in North Carolina). All homes met or exceeded the new HUD energy standards of October 24, 1994 (a few were actually built prior to that date). Nine homes were

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[2] Sample homes include 6 from New York, 8 from North Carolina, 5 from Alabama, 5 from Florida, and 9 homes from previous work sponsored by the Bonneville Power Administration Four of the homes were single-section, the rest were double-section.

manufactured in the Northwest under the Bonneville Power Authority Manufacturers Acquisition Program (MAP) to energy efficiency levels that exceed the new HUD standards. Indeed, the MAP homes include energy conservation measures associated with improved ADS performance, such as insulated underfloor ducts, a fact reflected in the higher efficiency estimates for these homes. The New York and North Carolina homes are also typical of their respective regions in many ways (for example, the New York homes have fossil fuel-fired furnaces and the North Carolina units are heated electrically, mainly with heat pumps), and generally are representative of ADS construction and installation practices outside the Northwest. However, it's worth reiterating that the sample is too small to suggest that the results are representative either of a location or of all manufactured homes.

Overall system efficiency for the new HUD code homes (the New York and North Carolina samples) averaged about 60 percent indicating a distribution system loss of 40 percent. The MAP homes tested earlier had a distribution system loss of 15 percent during the heating season. To place the findings for the typical HUD code homes in perspective, consider the profile of energy use for a home in the two study locations[3]. In New York, the heating season space conditioning bill for the typical home would run about $893. As graphically illustrated in Figure 1-1, equipment losses would account for $223 (predicated on the equipment operating at the rated value of 75 AFUE), the ducts losses generate $268 (30%) of the total bill, and envelope-related heating costs (including infiltration) the remaining $402 (45%). The same design in North Carolina (see Figure 1-2), in this case using electric resistance heating, would have space heating costs totaling $1,066 with the ADS responsible for $414 (39%) of the total and the envelope-related losses contributing $620 (58%) to the bill.

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[3] The examples in Figures 1-1 and 1-2 are base on a 1400 square foot home. The trunk duct insulation on half of the homes represented by the average is insulated with R-7 fiberglass insulation. The New York example assumes a gas-heated home with a local fuel cost of $0.58 and an envelope U_o-value of 0.079. The North Carolina assumptions are electric costs of $0.075 per kWh and a U_o-value of 0.096.

Figure 1-1 **Heating energy cost by end use (New York)**

Figure 1-2 **Heating energy cost by end use (North Carolina)**

Figure 1-3 **Heating season ADS efficiency losses by source**

The major sources of energy loss attributable to ADS that were measured in this study, listed in descending order of impact, are as follows: conduction through the duct walls, air leakage caused by gaps in the construction of the duct system, and higher whole house infiltration as a result of pressure differences that arise when the duct system is in operation. (See Figure 1-3)

The conductive losses were surprisingly high and can be traced to two root causes. First, most of the homes in the study are double section (consisting of two boxes) with a trunk duct in each box. The two trunk ducts are connected by a crossover duct running underneath the home and outside of the insulated envelope. Typically, the exterior ducts are wrapped with an R-4 or R-5 insulation. The high temperature difference between the duct temperature and the ambient, coupled with the relatively low insulation value, generates a portion of the conductive losses.

The second, and in some instances larger contributor to conductive losses is a result of holes in the underfloor insulation that allow ambient air to come in contact with the uninsulated trunk duct. Often, the last contractors to work on the home are the plumber or cable TV installer, trades that access the home through the floor cavity by cutting away part of the bottom board and insulation. This air pathway is often not resealed after the work is complete. Even a small hole can result in substantial air migration. The combination of uninsulated ducts and holes in the underfloor membrane greatly increase conductive losses.

1.4. Summary of the performance of ADS in the cooling mode

ADS cooling performance was gauged in twelve homes in the southern tier; five homes each in Florida and Alabama, and two homes in North Carolina. The Florida units reflected a statewide preference for delivering conditioned air into the living spaces via ceiling mounted registers, a practice not widely used outside the state. The Alabama homes were drawn from a group of homes built to the Good Cents standards, a voluntary energy efficiency program offered by Alabama Electric Cooperative. These homes were manufactured prior to the revision of the HUD Energy Standards. However, they are of a relatively recent vintage and, while lacking a whole house ventilation system, their level of thermal integrity exceeds the current HUD standards. The North Carolina homes were among the units included in the heating analysis described in Section 1.3. The Alabama and North Carolina homes all have underfloor ducts for air distribution.

Efficiency degradation in the cooling mode averaged about 18 percent for all homes, considerably less than the heating result but a significant loss none the less. Data for overhead duct systems (Florida homes) indicated an average performance reduction of approximately 24 percent and underfloor ducts (Alabama and North Carolina) losing about 14 percent on average (see Figure 1-4).

Figure 1-4 **Cooling season total system losses by source**

The superior performance of the underfloor ducts is due to several factors, including the following:

- Any leakage that occurs in the underfloor ducts, which are located above the belly insulation, lowers the temperature in the floor cavity and reduces the rate of conductive losses from the duct. Conversely, leakage losses from attic ducts, which are located above the ceiling insulation, are more easily vented to the outside and do not decrease conductive losses.
- The hot attic space will generate relatively high conductive losses from the ducts, particularly those sections near the attic air mass. The floor tends to be a more benevolent environment for ducts in the cooling season since the temperature in the crawl space is often below ambient.
- The modeling also suggests that duct leakage in the attic may create a positive pressure in the attic cavity relative to the living space. The pressure differential will drive attic air into the living spaces, which, even when blended with the air leaked from the ducts, will be warm enough to further increase the cooling load.

Having measured and explained the mechanisms behind the apparent superiority of underfloor ADS compared to overhead systems, it should be kept in mind that this analytical study did not attempt to quantify the impact of temperature stratification. Generally, in homes with low ceiling heights or ceiling fans, stratification is not a major concern. Where stratification is a factor, the home owner often compensates for a perceptibly higher temperature by turning back the thermostat. Ceiling mounted supplies will generally help mix the air. This factor might favor overhead ducts and minimize the efficiency advantages associated with the underfloor configuration.

Another challenge in estimating cooling season performance of ADS is how to accurately account for the impact of the latent component of the load on energy use. At present there is no consensus on this point, which is the subject of active debate within the engineering community. The analytical process employed here assumes the equipment operates until the sensible load is satisfied. The humidity is allowed to float, although in removing the sensible load moisture is extracted from the air in the home. This modeling strategy has its limits too; if the sensible load is removed and the relative humidity rises, the home owner might compensate for the perceptual difference in comfort by lowering the thermostat.

This is an important question, and how the latent component of the load is assumed to behave is a consequential issue because it impacts the relative magnitude of ADS-related losses (see Figure 1-5). In predicting the cooling performance of ADS, as in the heating analysis, losses are divided into conduction, leakage, and air infiltration components. Since the latent component does not lose energy through conduction, the relative magnitude of the losses changes depending on the modeling and home control assumptions. As shown on Figure 1-5, if only the sensible component of the load is considered, the efficiency reduction due to added whole building infiltration is about 5 percent out of a total 27 percent ADS-related performance degradation (17 percent of the total loss). With latent included, the loss due to added air infiltration climbs to

Figure 1-5 **Cooling season ADS efficiency losses by source** nearly 12 percent out of about 31 percent, or 38 percent of the total. How latent is handled in the analysis, therefore, will influence the kinds of measures considered to reduce ADS losses.

1.5. Recommendations for future ADS-related R&D

The following two questions define the R&D needs in the area of manufactured housing ADS: how large an energy penalty is exacted when manufacturers use an ADS for thermal transport?; and, if the penalty is large, what practical and cost-justifiable steps can be taken to reduce the losses? This study was a start at answering the first question and suggests some directions for addressing the second. Below is an abbreviated list of high priority recommendations for future ADS-related R&D:

- Expand the sample size to improve confidence in the results, particularly in cold climates where ADS-related energy losses are the greatest. Use the results to validate simulation models.
- Expand the field measurement to better identify specific sources and magnitudes of ADS losses. Include loss contributions due to crossover connections, trunk penetrations, perimeter ducts, furnace to trunk connections and other likely leakage sites.
- ADS performance varies greatly between homes. Identify which factory-installed and field-installed sealing strategies are successful, and which fail.
- Evaluate through testing the impact of simple, relatively inexpensive measures for improving ADS performance (such as wrapping the trunk duct with insulation). Use demonstration homes to accurately measure impact on energy use.
- Develop technologies designed to counter problems that often occur in field installation (such as snap-in, rigid crossover ducts). Explore design changes that reduce opportunities for ADS failures (such as reducing field penetrations of the bottom board).
- Characterize the impact of ADS-related thermal phenomena, such as distribution imbalances, air flow across the supply grille, temperature stratification, humidity levels, outlet vent location, etc.
- Conduct a research effort exploring the impact of ADS on other important energy-related areas, such as equipment operation, peak loads, and comfort.
- Conduct a field investigation of ADS in existing homes to measure if, how, and by what amount performance changes over time and develop methods for correcting common problems in occupied homes.
- Develop a simple test protocol that can identify ADS problems in the factory or during set-up.

2. Air distribution systems in manufactured homes

2.1. Overview

Up until the last few years, most manufactured housing research has focused on ways to improve the thermal envelope of the building and, to a lesser extent, the mechanical equipment. These are areas where it is easy to identify companies or organizations with proprietary interests, such as the insulation and heat pump manufacturers. New products and materials were developed that improved the integrity of the thermal envelope. Sensitized by a steady stream of consumer information, the market responded by demanding higher insulation levels and improved window products. The fixation with seeking higher R-values as a strategy for controlling energy use was formally sanctioned by the recent passage of changes to the HUD standards (October, 1994) that significantly raised the bar for mandated energy efficiency.

The attention of the scientific and home building community and power suppliers is now shifting to the poorly understood area of air movement. In this broad context, air flow issues fall into two subsets; ventilation designed to maintain a healthy living environment, and the transport of conditioned air for heating and cooling purposes. In nearly all new manufactured homes, conditioned air transport is generally aided by a system of ductwork designed to deliver heat and coolth to all areas of the home. Air is forced into the ductwork by a blower attached to the heating and/or cooling equipment and delivered to the living spaces via floor registers. A well-designed and constructed system is balanced maintaining an even temperature throughout the home. The concept is simple yet far from foolproof. Several anecdotal studies have hinted that the fabrication and installation of ductwork itself, and generally using air as a delivery mechanism, may exact a high energy penalty. Estimates vary but the average duct systems appears to reduce overall system efficiency by between 20 and 40 percent. Despite the fact that duct systems are installed in virtually every new manufactured home rolling off assembly lines throughout the nation, research in this area has lagged. The current work is a major step in correcting this omission.

The other important area related to air movement is whole house ventilation. The movement of air between the living spaces and outdoors is also not well understood but there is a growing consensus that manufactured homes are on average very tight, particularly when compared to their site-built counterparts. Improvements in building materials, constructing homes in climate-controlled factories, and a high level of construction quality control are to be credited. The issue has now shifted from building homes that leaked, with associated energy penalties, to homes that are tight with possible indoor air quality problems. HUD addressed this latter concern by requiring all new homes to have continuous ventilation, but in reality the ventilation characteristics of these homes are not well understood or quantified. Although ventilation and indoor air quality are not central to the current study, it is impossible to delve into the delivery of conditioned air through ducts without touching upon the ventilation issue.

The comments that follow will attempt to encapsulate what is know about duct-based thermal distribution. The description is by necessity broad since it builds on a small foundation of scientific inquiry. There are few contemporary studies dealing with ducts in manufactured homes and much of the data and observations related to duct system performance is, as noted earlier, anecdotal. (The project literature search, for example, turned up only three studies specifically addressing manufactured housing duct systems). There are plenty of opportunities to advance the state of knowledge; the challenge is to weed through the possible directions for the research and pursue those that exhibit the most promise.

Section 2.2 characterizes what is known about thermal distribution in manufactured homes; the report offers a synopsis of how ducts can impact energy performance. The reader should be aware of the fact that dividing areas of ADS-related energy loss into discrete categories is an oversimplification useful in structuring a research program and understanding the thermodynamics of the system. The operation of the system is such that many kinds of inefficiencies are occurring simultaneously. The relative impact on energy use of each changes over time, by location, as a function of home owner operation, and as a result of the physical characteristics of the home.

Next, in Section 2.3, a summary of energy performance of contemporary manufactured homes using duct systems is provided based on the topical literature. As will be evident, the data base for this discussion is small.

In Section 2.4, the study offers a profile of the kinds of distribution systems used by the industry. This section describes the design configurations, products, materials, and installation procedures common among manufacturers. The profile is a starting point for identifying improvements in thermal distribution systems.

Section 2.5 briefly describes the HUD's energy standards for duct systems summarized from the Manufactured Housing Construction and Safety Standards of October 1994.

2.2. How ducts impact energy use

In concept, the thermal distribution system is quite simple. The mechanical equipment heats or cools air that is fan forced into the ducts feeding the primary living spaces of the home. The air enters the living spaces through registers, generally located in either the floor or ceiling depending on the location of the duct system. In most installations, the return air supply enters through a grille on the face of the equipment closet. Few manufactured homes have a separate ducted return air system. Often, a relatively large proportion of the heating and cooling energy generated by the equipment is lost before it can provide useful space conditioning. Some of the ways energy is lost as a result of employing duct distribution are described in Sections 2.2.1 through 2.2.6: [4]

2.2.1. Conductive losses from the ducts

Typically, most of the duct run is located within the thermal envelope. In multi-section designs, the duct runs in the boxes are commonly connected by an insulated cross-over duct located outside the thermal envelope. This cross-over is subject to fairly high conductive losses, particularly at times of peak heating and cooling. Interior duct runs are not, however, immune to conductive losses. The size of the loss is a function of the amount of insulation adjacent to the ducts, the tightness of the envelope, and the difference in temperature between the ducts and ambient conditions. For example, ducts in homes manufactured for the Florida market are often placed in the attic, a location that experiences fairly high temperatures when cooling is needed the most. In many cases, the shallow attic spaces afford little room for insulating above the ducts.

2.2.2. Duct leakage

Sealing the seams of the ducts to prevent conditioned air from escaping into floor and ceiling cavities presents a challenge to the industry. Several sealing techniques are available, but the most effective are often expensive or too difficult to easily integrate into the manufacturing process. This is an area where further study is clearly warranted, particularly with regard to sealing the juncture of the duct system to the mechanical equipment and the connection of the boot to the main trunk run in floor systems. In addition, duct leakage may change after the home is transported to the site and as a result of material degradation over time. Some duct tape sealants are particularly prone to this latter problem. However, it is not clear to what extent the leaks translate into energy penalties when the ducts are inside the thermal envelope and some of the heating and cooling energy lost through the leaks remain within the home.

2.2.3. Ducts and whole house infiltration

When the blower fan switches on, the pressure within the home changes, often causing an increase in the rate of air movement through leaks in the thermal envelope. Several researchers have attempted to quantify the impact of fan-induced infiltration using site-built examples. As noted earlier, the results from site-built homes often cannot be extrapolated to manufactured homes where construction methods typically provide a tighter envelope. Pressure imbalances in the system can aggravate the leakage problem.

2.2.4. System imbalances, register location, and comfort

Proper planning of thermal distribution systems require that the ducts be sized according to the needs of each of the spaces serviced and that the registers be

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[4] A more comprehensive categorization of air distribution loss mechanisms is provided by Modera, et. al. (see reference 6 in the bibliography).

placed in areas where the air flow is not impeded. This is difficult to achieve with current practices. Generally, duct runs are of a uniform cross-section construction, not graduated as would be dictated by the needs of the individual spaces. The result may be noticeable room to room temperature variations. The air flow imbalance can be further exacerbated by poorly located registers and/or damaged grilles (e.g., bent blades). If cold spots result, the common home owner response is to turn up the thermostat, prolonging the operation of the space conditioning equipment and effectively wasting energy.

2.2.5. Equipment cycling, equipment sizing, and peak loads

The decrease in system efficiency due to the ducts must be compensated for in the selection of the mechanical equipment. The manufacturers and/or mechanical contractors specifying the equipment explicitly or intuitively include in the sizing analysis a safety factor to assure that, even with the duct and other system losses, the home owners will be comfortable. In most instances, the capacity of the equipment far exceeds the design load. (This is true in the selection of both heating and cooling equipment although, except in the case of heat pumps, cooling equipment is available in a wider range of capacities, allowing a closer match to the actual load.) Oversizing has two primary disadvantages: increased equipment cycling, resulting in a lowering of the overall operating efficiency of the equipment; and an increase in the home’s peak load. In a recent study of manufactured homes in Alabama, the impact of a wide range of energy conservation options on peak load profiles was analyzed overall a three year period. The single most effective strategy for saving energy and reducing peak loads was properly sizing (i.e., downsizing) the mechanical equipment. [5]

2.2.6. Off-cycle losses

The air distribution system-related energy losses that occur when the blower fan is off, referred to as off-cycle losses, are not well understood and elude easy quantification. At times when the mechanical system is not operating, the temperature within the ducts drifts toward ambient through a combination of heat flow due to conduction, radiation, and leakage. Exterior ducts exposed to higher temperature differentials are particularly prone to these kinds of losses. When the equipment switches on, the load to be satisfied now includes the ductwork itself. In addition, some duct configurations lend themselves to off-cycle thermosiphon losses. Air in the living space flows back into the ducts due to vertical temperature gradient (that is, convective air currents). This phenomenon effectively increases the envelope area of the home. Thermosiphoning is mainly a danger in homes with overhead ducts common in many southern states, such as Florida.

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[5] Levy, Emanuel; Marisha Chilcott; et. al., 1994, ***Good Cents Manufactured Home Study***, P654-080, Washington, DC; National Rural Electric Cooperative Association

2.3. Energy performance of ducted air systems

As is evident from the annotated literature review (Section 5), there is a dearth of manufactured housing-related air distribution citations. Nowhere is the lack of information more noticeable than in the area of performance data collection and analysis. The handful of studies that have sought to quantify the impact of air distribution systems on manufactured housing energy performance are modest in scope and from a research perspective can only be characterized as anecdotal. Taken together they do not begin to reveal the magnitude nor complexity of the energy use problems associated with the air distribution system.

Most of the data collected in regard to the reduction in energy efficiency caused by the distribution system was extracted from site-built housing studies. The table below summarizes the findings of a handful of such studies. Performance degradation, as expressed as a percent of total energy use, ranged from a low of 12 percent to a high of 40 percent. The lower value considered only the change in efficiency associated with the leakage from the ducts and neglected the other kinds of loses described earlier. There is reason to believe that manufactured homes would have values that are different from those noted on the table based solely on the dissimilarities in construction practice. The magnitude of the differences and manner in which they are manifest are the subject of the accompanying research effort.

Table 2-1 **Summary of ADS efficiency**

Study (date, bibliographic reference)	Estimated percent reduction in efficiency
Field measurements of 24 electric homes (1993,2)	*29*
Improving the efficiency of air distribution systems (1992,3)	*25 to 40*
Thermal distribution in small buildings (1992, 5)	*30 to 40*
Electric appliance pilot project (1990, 11)	*25 (cooling)* *16 (heating)*
Residential infiltration and duct leakage (1989, 12)	*12*
Mobile home heating, cooling and fuel burning study (1979, 20)	*15 single section* *22 multi-section*

In summary, there is every reason to believe that the distribution of the losses will vary between site-built and manufactured homes. For example, the typical manufactured home has most of the ducts within the conditioned envelope. This tends to minimize the conduction loses and allows other loses to be reclaimed by the conditioned space. Conversely, when ducts are placed outside the home -- the most common exterior application is the cross-over duct in a multi-section unit -- it is fully exposed to the elements. Cross-over ducts experience a high conducive loss. Further, plant-applied materials are subject to quality control checks and flaws are readily exposed. Unfortunately, the same cannot be claimed for the site-installed material.

The ducts in manufactured homes are installed quickly and leaks in the duct work are not uncommon. Small openings are prone to become larger openings if the sealing materials have a short useful life. In addition, the home is subject to shaking and jarring as it is transported from factory to retail lot and eventually to the site. The jostling may take its toll on the overall air tightness of the duct system. Another problem endemic to manufactured homes is the inefficiency that results from improper placement of duct registers or installation of the cross-over duct. When home owners complain that the heating and/or cooling equipment is not providing sufficient space conditioning there may be any of a number of root causes including floor registers covered by furniture, improper system layout and sizing, or a cross-over duct that is not securely connected to the main trunk line.

Other differences between site-built and manufactured homes relate to geometry and design. Manufactured homes are typically long, thin structures. Imbalances in the duct design can easily translate into over-conditioning of spaces close to the equipment and under-conditioning of other living spaces. The home is almost always considered as one zone in planning the distribution system. After all, a two-story manufactured home is a rare sight. As a result, stratification and thermosiphoning are more likely to be problems in site-built structures. Upon close inspection, the two homes types share few common denominators in regard to thermal distribution system design, materials, and installation. Extreme care must be exercised on attempting to apply the results of studies based on site-built homes to manufactured designs.

A handful of studies have sought to evaluate manufactured housing air distribution performance specifically. Within the context of this discussion, one study of particular note was prepared by Ecotope for Bonneville Power Administration as part of the Super Good Cents program. In that work, distribution systems in manufactured homes were analyzed using a technique called coheating. Coheating allows the energy use of the home to be gauged with and without the duct system. The difference between the two figures represents the duct losses. Typical construction was found to engender an average efficiency reduction of 30 percent. That is, 70 percent of the usable heating and cooling energy produced by the equipment was delivered to the spaces to be conditioned. This finding was based on testing of conventional underfloor duct systems. Systematic duct sealing techniques reduced the loss by half to 15 percent. While the sample of homes tested was small, this study corroborated the growing body of evidence that energy loses due to the distribution system can be significant. Quantifying the loses and searching for ways to reduce their severity are the subject of the other tasks of this program.

2.4. Current construction practices

The building block of manufactured housing architecture is the long, narrow wood-framed box sitting atop a metal chassis. Most homes are composed of one or two boxes, but three or even four boxes are not uncommon. The box shape itself and the manner in which living spaces are grouped along the long axis of the box dictates the location and layout of the duct system. Federal interstate transportation regulations limit the height of the box, assuring that the attic and floor cavities are shallow and implicitly restricting the area available to the distribution system. The vast majority of new manufactured homes have a single straight underfloor duct running the length of the home near the center of the box, a sort of mechanical spine with boots placed at 90-degrees to the main trunk line feeding up to floor registers directly above. Most are of uniform cross section, 5 inches by 12 inches being typical dimensions. The mechanical equipment is typically located in a closet directly above the main duct. The advantages of this design are so compelling in fact -- it is easy to fabricate, quick to install, and very inexpensive -- that the methods and materials used in a plant in Maine are virtually identical to those used by factories in Southern California. When two boxes are involved (multisection homes), each box is equipped with a main trunk connected by a cross over duct installed in the field.

There are of course variations on this theme. Some plants utilize branch ducts to feed registers located at the perimeter of the home. The branches are run in the space between the transverse floor joists. This is more expensive than the typical case described above and arguably more energy efficient. Another variation that offers superior performance but at higher cost is the graduated duct system where the cross sectional area is tapered to deliver a more measured air volume in proportion to the individual living space needs. This design has its proponents and is more common among manufacturers of upper end homes. Although no data is available on the demographics and distribution of underfloor systems, they appear to hold the lion’s share of the market in every state except Florida.

Florida is the home of the overhead duct system. By most accounts, it is the standard in the state in the same way that underfloor systems are typical elsewhere. The popularity of overhead ducts is due to the traditional practice of delivering cold air from above. (The efficacy of this configuration is discussed as part of this research effort.) The overhead systems are usually fed from equipment installed in the field, increasing somewhat the amount of site labor. The success of overhead ducts in Florida has led to its adoption in other regions, particularly by manufacturers that have plants in Florida and are conversant with the associated construction methods. The potential market for overhead ducts, however, is limited to areas with much larger cooling than heating loads.

Standard equipment in most manufactured housing facilities is a duct fabricator, a simple metal folding device that transforms a coil of sheet aluminum into a rectangular duct of any length. The ends of the main duct line are sealed by folding the metal to form a flap and applying tape. Boots are made from shorter pieces of the same material and connected to the main duct line by bent tabs and duct tape. In a minority of instances, pressed fiberglass duct board is used for the duct runs although the higher cost, relative to sheet aluminum, and health concerns related to exposed fiberglass fibers, has slowed acceptance of this product. The major fear is that fibers of the insulation will shed from the exposed inner surface or the duct and enter the air stream and the living spaces of the home. A link between fiberglass use in such applications and cancer risk has yet to be scientifically established, although the potential future liability is a barrier to this product. Rigid aluminum and fiber board ducts are employed principally in underfloor duct runs, although the cross over connector, supplied by the on-site installer, is typically steel helix reinforced circular flex duct with an insulated shell. Insulated flex duct is also the product of choice in overhead systems where the forest of trusses render rigid duct materials cumbersome.

In the typical installation, a single straight run of metal duct is fabricated in a length sufficient to reach the furthermost registers. In extreme cases, this duct can measure 65 feet or more. The duct is placed at or near the center of the box between the two supporting metal I-beams that run longitudinally and are an integral part of the chassis. This duct is generally uninsulated but encased within the floor cavity between the insulation below and the subfloor above. The main trunk is tied to the floor joists with straps. The plywood floor decking is marked with locations of the registers. In rather rapid operation, the register openings are cut and the boot installed to locate the intersection with the main and the boot. The hole in the relatively thin aluminum main duct is cut with a knife and the boot connected by folding the flanges of the boot around the opening and sealing with tape.

Sealing the ducts with duct tape is a questionable practice given the short service life of many of the most popular and least expensive products on the market. Sealing techniques that require more expertise are more expensive, or may slow the production process. For example, glass fabric and mastic or mechanical fasteners are avoided. The entire operation of fabricating and installing the duct system is measured in minutes rather than hours at a total cost of materials and labor of a few hundred dollars per home. This ultra-low cost baseline represents a formidable design constraint in the quest for more energy-efficient alternatives to current distribution system practices.

2.5. The regulatory environment

Air distribution systems are covered by the HUD Manufactured Housing Construction and Safety Standards in Section **§3280.715 Circulating air systems**. The section contains five parts: supply systems, return systems, joints and seams, supports, and registers or grilles. The provisions cover sizing, material use, connections, and design guidelines. The most recent changes to the standards that went into effect October 1994 left this section of the standard virtually unchanged. Highlights of the provisions are discussed below.

- Allowable leakage on the supply side is governed by a paragraph that stipulates that " . . . the static pressure within the duct must be at least 80 percent of the static pressure measured at the furnace casing." However, not every home must be tested, and this requirement extends only to factory-installed air distribution systems. Joints and seams are required to be "substantially airtight."

- Field-installed cross-over ducts must not be in contact with the ground and must be insulated to a level of R-4 for floor mounted and R-6 for ceiling mounted configurations. This latter requirement is climate independent. Exterior ducts must also be wrapped with a vapor barrier having a perm rating not greater than 1 perm.

- Provisions must be made for return air to the equipment, although a louvered door on equipment closet suffices and is typical. Since living spaces are not serviced by return air ducts there must be an unobstructed air pathway back to the equipment closest. Undercutting doors and through-the-wall transfer grilles are accepted practices. The standard requires undercuts to be at least two and no more than two and one-half inches in height.

3. Performance of air distribution systems in the heating mode

3.1. Overview

This chapter summarizes field measurements and analysis which describe the heating system efficiency of the ADS in homes manufactured to 1994 HUD thermal standards (homes in New York and North Carolina) and the Bonneville Power Authority Manufacturers Acquisition Program (MAP). Data collection and analysis of homes in the heating mode was a collaborative effort of Ecotope, Inc., Synertech Systems Corporation, and North Carolina Alternative Energy Corporation. Ecotope is the principal author of the testing protocols and led the field data acquisition and analysis effort.

The results reported below are based on the field testing of eight homes in North Carolina and six homes in New York. A single testing protocol was used for these 14 homes. All the units were built just prior or subsequent to the promulgation of the new HUD energy standards enacted in October 1994 (referred to within this study as HUD-code homes). The results from these homes are compared with nine manufactured homes built to MAP. Although the MAP homes were manufactured prior to October 1994 their insulation levels are in all cases higher than the HUD-code units. The authors of the MAP requirements included requirements specifically designed to improve the performance of the ADS (such as more stringent duct insulation and air sealing measures). This is reflected in the generally excellent ADS performance results that characterize the MAP homes. It is possible to produce homes with ADS performance that exceed MAP homes, although the cost to do so may prove to be prohibitive. Consequently, the performance of the MAP homes in the heating mode are considered an upper boundary on what may be practical given current manufactured housing practices.

The protocol used in collection of data for the HUD-code homes combines a physical audit of the home with duct air leakage and pressure measurements, and temperature monitoring of the home and duct zone during furnace operation. Each home's steady-state heat delivery efficiency [6] is estimated empirically. The steady-state heat delivery efficiency is also modeled mathematically. The empirical and modeled results are combined and transformed into a system efficiency which takes into account off-cycle losses and recovered heat [7]. The

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[6] The heat *delivery efficiency*, as defined by ASHRAE, is the ratio of the total useful heat delivered to the supply registers while the fan is on, divided by the power input to the furnace.

[7] *System efficiency* is an indicator of overall performance. It accounts for energy that may be lost during transport through the ducts but eventually flows back into the living space (referred to as regain) as well as other secondary energy effects (such as added whole house air infiltration) caused by the operation of the ADS. Because the system efficiency incorporates all losses as well as gains, it is a more realistic indicator of the performance of the duct system than is *delivery efficiency*.

transformation is facilitated by additional data extracted from prior research (Davis, Palmiter, and Siegel 1994).

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 in this report is still very modest, and some of the testing techniques are best described as experimental. However, the efficiency analysis provides a reasonable estimate of energy losses and possible savings from design changes.

Design changes can have a dramatic impact on ADS performance. For example, MAP mandated major changes in floor insulation strategies. These changes greatly reduced conductive losses from ducts, since the manufacturers usually upgraded the underfloor insulation from R-11 or R-19 to R-33 and were required to wrap (previously uninsulated) underfloor heating ducts with R-5 insulation. More care was also taken with sealing the end-cap of the trunk ducts and taping heating register risers to the trunk duct. These changes did not completely eliminate duct losses, but they proved cost-effective.

The method for predicting system efficiency described above was used for analyzing the data collected in New York and North Carolina. The model includes factors for direct air leakage, conductive losses, and added air infiltration due to the interaction of the furnace fan with natural infiltration. Field validation was accomplished with data from homes built to MAP specifications. The model is summarized in Palmiter and Bond (1994).

Data was collected under MAP using a coheat test, a procedure designed to isolate the performance of the distribution system. Short-term coheat tests, although time-consuming and expensive, have proven very powerful in describing efficiency penalties associated with forced-air electric heat in various homes. Results of these tests are summarized in Olson et al (1993) and Davis et al. (1994).

In the coheat procedure, a home is alternately heated with the furnace and then with an array of small (1.5 kW) heaters placed in each room which has a supply register. The test alternates between these two methods every two hours, collecting temperature and energy usage data every second. An automated control algorithm controls the furnace and coheaters to keep the home at essentially the same temperature during the alternating cycles. The ratio between the average power in the two heating modes is the overall system efficiency. The test periods are relatively short, minimizing thermal mass effects. Additionally, the test is conducted at night to minimize solar gain effects.

Because of time and budget limitations, a less demanding protocol was used for the North Carolina and New York sites. This procedure furnished the inputs necessary for estimating steady-state heat delivery efficiency. The steady-state heat delivery efficiency is a best-case estimate of overall distribution efficiency since measurements are taken after the furnace has fully warmed up and the floor structure, ducts, and insulation are heated to maximum levels. Because this measurement does not address conductive losses during warm-up, and because it does not include heat recovered back into the home during furnace off-cycles, further adjustment was needed to estimate long-term system efficiency. An empirically-based transformation was applied to the steady-state heat delivery efficiency to calculate system efficiency for the North Carolina and New York homes. The transformation relies on the relationship between heat delivery efficiency and steady-state heat delivery efficiency in the MAP homes tested with the coheat procedure, and it also includes a factor which describes the amount of heat recovered into the heated space during furnace off-cycles. The combustion efficiency of fossil-fueled furnaces is taken from manufacturers' information and is factored into the final efficiency estimate.

The amount of heat recovered during off-cycles is probably higher in the MAP homes, since they have more underfloor insulation and less duct leakage than the HUD-code homes. Therefore, since the factors that are used to convert steady state 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.

3.2. Heating climate protocol description for the new HUD-code manufactured homes

The heating protocol included a physical house audit, various measurements of house and duct tightness, pressure diagnostic tests, and measurements of heating system performance (air handler flow, supply register flow, and a set of temperature measurements taken during furnace operation).

The physical house audit was important in determining the heat loss rate of the homes so that their energy use over a normal heating season could be estimated. The field crew was also charged with listing the area and insulation value of the ducts, inasmuch as this could be determined from direct observation and manufacturers' specifications. The duct system information was required to estimate conductive losses from the ducts into the underfloor buffer space and to the crawlspace.

The Minneapolis Blower Door Model #3, the Minneapolis Duct Blaster ™, and a Minneapolis 2-channel digital pressure gauge was used for all measurements. Blower door tests are now an accepted method of characterizing home air leakage. The blower door is a large calibrated fan which is used to depressurize or pressurize a house to a given level (reference pressure). When the house has reached this reference pressure with respect to outside, the amount of air leaving through the blower door fan and hence being pulled through all the leaks in the house is measured and is converted into a whole house leakage rate (commonly expressed in air changes per hour, or ACH). The Duct Blaster ™ is a small version of the blower door which is used to pressurize or depressurize the duct system to a given level, at which time the amount of air flowing through the fan is measured. Duct leakage is commonly expressed in cubic feet per minute (cfm) rather than in ACH.

House tightness was measured with the home depressurized to approximately 25 pascals and 50 pascals with respect to outside. A Minneapolis Duct Blaster ™

was used to directly measure duct tightness in the sealed duct system at these reference pressures. External duct leakage was also determined by running the blower door simultaneously with the Duct Blaster ™ to approximate a pressure gradient of zero across the floor plane. This technique is relatively new, but has become an accepted method of describing duct losses. Since some of the heated air that leaks from ducts returns to the home's interior, it is inaccurate to describe this portion of the total duct leakage as contributing to the reduction in overall heating system efficiency. Only external leakage is listed in this report. The blower door and Duct Blaster ™ results are very useful in comparing any set of homes tested with other sets of homes (whether they are manufactured or site-built homes).

The advantage of using a single tightness measurement at a given reference pressure is that vagaries in the different homes can be condensed into one leakage measurement. A home may have noticeable localized leaks but overall be relatively tight. The overall leakiness of the home is what is important in estimating additions to the home's heating load resulting from air infiltration.

Blower door tests were performed in accordance with the procedure outlined in the Minneapolis Blower Door Manual (Energy Conservatory 1992). The blower door tests were conducted in depressurization mode in order to minimize any additional leakage from backdraft dampers that would be opened during blower door tests in pressurization mode. The houses were tested in an "as found" condition, except in houses with make-up air ports ducted into the furnace cabinet. In these homes, such ports were taped off. The make-up air duct represents a sizable intentional return leak, and is regarded as an artificial addition to the building shell leakage. If the home had a wood stove and/or fireplace, their dampers were sealed during the test. A smoke stick was used to pinpoint areas of significant local leakage.

The blower door tests were conducted at two reference pressures: -25 pascals and -50 pascals (house pressure with respect to outside). Two-point blower door tests are becoming more common, since field calibration exercises such as those detailed in Palmiter and Bond (1994) have shown that the blower door tightness over a wide testing range (ΔP between house and outside of 8 to 64 pascals) is adequately described by a two-point test.

The blower door was checked for acceptable flow exponents (in the range of 0.5 to 0.7). Because conditions were sometimes windy, or there were other problems, some blower door tests had to be repeated. The Duct Blaster ™ tests also had to be repeated in some cases because the pressure drop across the Duct Blaster™ was out of the instrument's normal calibration range.

Tracer gas decay tests were also performed in these homes to estimate effective ventilation rates. The effective ventilation rate is the rate at which outside air actually dilutes and displaces a pollutant introduced into the indoor air. Depending upon the characteristics of indoor pollutant generation, distribution of leaks in the house, wind effects, and the relative size of the stack effect, the effective natural ventilation rate of a home can be very different from the average ventilation rate used in heat loss calculations. An infrared gas monitor was used with sulfur hexafluoride (SF_6) gas to measure effective ventilation rates in these homes, first with the air handler running and then with it turned off. Indoor air was mixed in each room with portable fans in order to minimize stratification. The tracer decay approach tends to underestimate effective ventilation rates in homes, because there is some re-introduction of tracer gas from the underfloor area back into the house.

For the North Carolina sites, the pressure in the underfloor interstitial space was recorded while the blower door was operating. These measurements offer a quantitative and qualitative evaluation of how exposed this area is to the outside.

Other pressure diagnostic tests were performed to more precisely characterize air flow and energy performance. Overall house envelope pressure was measured with the air handler fan on and off to determine house pressurization and depressurization under these conditions. Pressures across bedroom doors were also measured with the doors closed to measure the magnitude of bedroom pressurization.

Pressure pan tests were also performed at these homes to qualitatively describe duct leakage. The pressure pan is becoming more commonly used to describe localized air leaks. The pan is used with the blower door in depressurization mode. Each register is tested individually. If there are no leaks near where the pan is placed, there will be no pressure drop across the pressure pan. However, if there are leaks, extra air being pulled into the leak due to the depressurization of the house and the duct system will cause a positive pressure to register on the pressure pan. If the leak is very large, the pressure pan reading can be as high as 5 pascals. When the leakage is limited, pressure pan readings are 1 pascal or less.

The protocol included a procedure for measuring temperatures in the home, in the interstitial space, at the furnace “return” air intake and supply “plenum”, and in the crawlspace during normal furnace operation. The temperature measurements were made using small portable dataloggers and temperature probes placed at various locations in and around the home. The purpose of these measurements, collected at one minute intervals, was to determine the environment in which ducts reside and to estimate the effects of duct air leakage and conductivity losses on heat delivery efficiency.

The flow across the air handler was measured so that the duct leakage could be expressed as a percentage of this flow. This flow was measured using two techniques: temperature rise across the equipment coupled with a measurement of equipment input energy and a technique whereby the Duct Blaster ™ acts as a helper fan, supplying all air to the furnace blower. Both of these techniques have limitations, so an indirect calculation of air handler flow (relying on the sum of supply register flows and the exterior duct leakage) was also made.

In New York, two sets of tests were conducted, one using the protocol described above and a second set designed to gauge performance over a longer time span.

The long-term tests consisted of instrumenting each of the units with an eight-channel data logger that produces time series data records at intervals ranging from one minute to one hour. The four digital channels monitored furnace run time, furnace firing counts, HVAC fan run time, and number of times the entry door was actuated over the period. The four analog channels measured temperature between the bottom board and slab, temperature within the bottom board, indoor air temperature close to the thermostat, and return air temperature in the furnace cabinet. Outdoor air temperature was measured on two sites instead of temperature below the bottom board. Monitoring was conducted from February through early May 1995.

3.3. Field survey of new HUD-code homes

The following section describes the results of the field tests in North Carolina and New York. As will be evident from the data, the results for individual homes can vary significantly and, when viewed in isolation, offer a distorted picture of ADS performance. Therefore, the results of field testing and analysis are expressed for the entire group of HUD-code homes using both average and median values. However, even these values must be viewed with caution given the small sample size. For comparison purposes, condensed results from Northwest homes are provided in a separate section because these homes were built to very different standards and, as noted earlier, were subject to a different testing protocol.

The North Carolina homes are atypical of current construction practices in that all but one are equipped with heat pumps. Consequently, the tests in this protocol were performed with the system in backup (resistance) heating mode to isolate the operating characteristics of the ADS from the heat pump operating characteristics. All of the New York homes were heated with fossil fuel furnaces (natural gas or propane).

Of the 14 HUD-code homes participating in this study, eight were sited in North Carolina, and six were set up in New York. One of the homes in North Carolina was a modular home, although similar in design and construction to HUD-code housing. Its data were left out of the heat delivery efficiency summary because the home is not technically a manufactured home. All the homes meet the new HUD thermal specifications, although a few were built prior to the new law and lack the now mandated whole house mechanical ventilation system. Five of the six New York homes were originally tested at a retail lot. The multi-section homes were connected and temporarily sealed at the marriage line. However, some tests were repeated for two of these homes after they had been moved to a permanent site. Only one home in New York was tested at the building site prior to occupancy.

3.3.1. House characteristics, North Carolina

With the exception of two homes, the North Carolina sample consisted of multi-section units manufactured after the new HUD standards were enacted in October 1994. The two homes built prior to the promulgation of the new standards, however, were constructed with an upgraded insulation package that meets the thermal provisions of the new standard. With the exception of one home tested at a retail sales center, the units were tested after set-up and were occupied at the time of the tests. An attempt was made to test homes from several manufacturers.

The homes ranged in size from 956 to 1832 square feet. The homes were built by six different manufacturing plants in North Carolina. Typical construction was 2 inches by 4 inches walls with R-11 fiberglass batt insulation, and transverse floor joists with R-22 fiberglass batt insulation. Ceiling insulation was either blown rock wool or fiberglass batt ranging from R-26 to R-30. All the homes used vinyl siding for their exterior sheathing and the roof covering was made of either fiberglass or asphalt shingles. The typical foundation was dry stacked concrete piers. All but one of the homes had vented masonry skirting around the perimeter of the foundation.

The interior wall and ceiling surfaces were typically gypsum wall board, the floors were carpeted except for the vinyl flooring in the kitchen, utility and bathrooms. All the homes had at least 66 percent of the ceiling area as cathedral-type construction, and a few were 100 percent cathedral. The typical floor-to-ceiling height along the interior face of the side walls is 7.5 feet. Windows were all metal framed, and typically a single pane exterior window combined with an inside-mounted storm window with a gap of 3 to 4 inches between the glass layers. Three of the homes had double glazed “thermopane” windows. Doors were metal with insulated cores containing single- or double-glazed lights. A few homes had skylights made of two layers of plastic glazing set in a wooden frame.

All but one of the North Carolina homes have split system heat pumps for space conditioning. The units are rated for either 3 ton or 3½ ton capacity (which is oversized for this climate). Refrigerant is routed from an outside compressor unit to the inside heat exchanger coil mounted in the air handler. Heat pumps have traditionally had a low share of the space conditioning market so this sample characteristic is most unusual. Although no attempt was made to locate homes with heat pumps, the high saturation in this sample could be due to recent electric utility promotions. One home was heated with an electric furnace and was cooled with window air conditioners. To comply with the new HUD ventilation requirements, each manufacturer had chosen a strategy designed to introduce outside air into the air handler compartment through a dampered duct, and to exhaust air to the outside through a wall vent.

The typical truck duct is located in the interstitial space between the subfloor and the floor insulation and measured 4½ inches or 5 inches by 12 inches. The metal duct runs the length of each home and is anchored to the bottom of the floor joists by straps. The living spaces are fed by metal riser boots located directly over the trunk duct and stapled to the floor surface. The connection to the trunk was made by bending metal tabs on the boot into the trunk. In only two of the homes were these sealed, in both cases with foil tape. Three homes used perimeter ducts connected to the trunk duct with 4 inch diameter flex duct. The two trunk ducts, one in each box, were connected by a single 12-inch diameter, insulated flex duct crossover. The crossover was routed from directly below the air handler on one side to near the midpoint of the trunk of the other box.

3.3.2. House characteristics, New York

All the New York units are heated by forced-air gas furnaces. Propane is used to heat all but the NY-1 home, which is fueled with natural gas. The units range in size from 1053 to 1723 square feet, and five of the six are double-section units (NY-3 is a single-section home and therefore lacks an external cross-over duct). The homes were manufactured in plants located in New York and Pennsylvania.

The homes in New York were all unoccupied at the time of testing. One was a park model and came fully furnished. The typical foundation consists of a six inch uninsulated poured concrete pad with intermediate support provided by dry stacked concrete block piers. Concrete blocks are also dry stacked to form a skirt along the entire perimeter of the building. Venting of the skirt (some of the homes lacked skirting at the time of the tests) is through four 8 inch x 10 inch vent openings placed on the long sides of the building. An 18 inch x 36 inch access panel is provided on each of the short sides of the home.

The typical roof is a gable design. Walls are framed with 2 inch x 6 inch stock except at the interior partition, where there is 2 inch x 3 inch framing. The exterior walls and ceiling are insulated with 6 inch fiberglass batts. Exterior walls are sheathed with 1/2 inch compressed wood chip board and wrapped in building paper. The entire wall assembly is covered with vinyl siding. The roof is sheathed with 1/2 inch plywood, covered with roofing paper and finished with 3-tab asphalt shingles.

Interior ceiling surfaces are 1/2 inch gypsum board and they follow the gable roof line. Wall surfaces are 3/8 inch finished gypsum or 1/8 inch simulated wood paneling. Floors are either sheet vinyl (kitchen, utility, and bathrooms) or carpeted.

Windows are double-glazed, aluminum-reinforced vinyl with one tilt sash and one fixed sash. Most of the homes had skylights, usually constructed of double-glazed PVC plastic in aluminum frames. The front and rear doors are metal with insulating foam cores and double-glazed lites.

The buildings are heated by natural gas-fired, forced-air furnaces rated with 95,000 Btu/hr input being a typical size for multi-section units. Heated air is supplied through an enclosed galvanized sheet metal duct system which is housed in the floor cavity (NY- 6 has fiberglass ducting). The duct system is composed of a trunk line that runs along the long axis of each half of the home and branch lines feeding individual rooms. Heat is provided to each room along the outside wall, typically below a window. The two trunk ducts are connected by a twelve inch diameter flex duct which rests on the ground in the crawlspace area. Return air from the interior is unducted. However there is a make-up air duct extending from the roof into the furnace cabinet. This duct serves as the source of whole building ventilation as required by the HUD-code. Combustion air is drawn from an opening into the crawlspace directly below the furnace closet. The building is also spot ventilated by small manually-controlled units in both baths, and a manually-controlled range hood fan.

3.3.3. Energy features of the HUD-Code homes

The envelope thermal integrity of the test homes is of interest since simulations of yearly energy use and savings due to possible design changes depend on an accurate characterization of the heat loss rate. The home's U_o-value (last column of Table 3-1) describes the weighted average conductive heat loss rate of the home per square foot of surface area of all components (wall, floor, window, door, ceiling, and ducts). The U_o-value is the figure of merit for the HUD thermal specifications. HUD divides the United States into three thermal zones with different maximum allowable U_o-values. According to the 1994 HUD thermal specifications (HUD 1994), the highest allowed U_o-value in HUD Thermal Zone 2 (which includes North Carolina) is 0.096 Btu/hr °F ft^2. The highest allowed U_o-value in Thermal Zone 3 (which includes New York) is 0.079 Btu/hr °F ft^2. The U_o-value does not include the contribution to heat loss from air leakage, although it does include an explicit contribution from duct conductive losses.

In most cases, the homes in this study come in under the maximum allowed U_o-value and the deviation from the maximum allowed U_o-value is small. The North Carolina homes are built to more stringent thermal standards than required by the HUD standards. This could be because these homes were constructed so that they could be sited in either Zone 2 or Zone 3.

The U_o-values for each home were found using nominal R-values reported on the home's HUD dataplate and from window manufacturer model listings. In many cases, the information was verified by the manufacturers that built the homes in this study.

Table 3-1 **Physical audit data**

Home ID	Date of Manufacture	HUD Zone	Home Type	Floor Area (ft^2)	House Volume (ft^3)	Glazing/ Floor Ratio (%)	Total Length of Ductwork (ft)	House U_o-value (Btu/hr° F ft^2)
NC-1	3/16/94†	2	double section	*1843*	*15454*	*11.3*	*191*	*0.080*
NC-2	10/14/94†	2	double section	*1296*	*10067*	*12.6*	*90*	*0.083*
NC-3	12/2/94	2	double section	*1843*	*15454*	*12.3*	*164*	*0.087*
NC-4	11/16/94	2	double section	*960*	*6837*	*11.6*	*88*	*0.079*
NC-5	12/9/95	2	double section	*1689*	*13501*	*12.0*	*94*	*0.076*
NC-6	11/17/94	2	double section	*1471*	*12393*	*8.2*	*97*	*0.075*
NC-7	1/19/95	2	double section	*1515*	*11803*	*8.5*	*118*	*0.077*
NC-8	1/4/95	2	triple section	*2192*	*17734*	*10.4*	*214*	*0.085*
NY-1	12/21/94	3	double section	*1685*	*13887*	*9.2*	*222*	*0.076*
NY-2	11/11/94	3	double section	*1648*	*13611*	*12.4*	*210*	*0.081*
NY-3	11/4/94	3	single section	*1120*	*8600*	*10.8*	*69*	*0.084*
NY-4	1/11/95	3	double section	*1053*	*8589*	*10*	*103*	*0.085*
NY-5	7/6/94†	3	double section	*1371*	*10660*	*7.3*	*104*	*0.072*
NY-6	1/13/95	3	double section	*1723*	*13276*	*9.1*	*198*	*0.067*
North Carolina								
	Average value			*1601*	*12905*	*10.9*	*132*	*0.080*
	Median value			*1602*	*12947*	*11.4*	*107*	*0.080*
	Standard deviation			*379*	*3444*	*1.7*	*50*	*0.004*
New York								
	Average value			*1433*	*11436*	*9.8*	*151*	*0.077*
	Median value			*1510*	*11968*	*9.6*	*151*	*0.079*
	Standard deviation			*297*	*2483*	*1.7*	*66*	*0.007*
Combined averages								
	Average value			***1528***	***12276***	***10.4***	***140***	***0.079***
	Median value			***1570***	***12835***	***10.6***	***111***	***0.080***
	Standard deviation			***344***	***3054***	***1.7***	***56***	***0.006***

† Built prior to the promulgation of the new HUD standards.

Proper specification of window U-value is crucial to describing the home's overall heat loss rate, because windows lose heat at a rate an order of magnitude greater than opaque components. However, thermal ratings for the same glazing product can vary depending on the testing procedure used by the product manufacturer.

This situation has improved substantially with the publication of the National Fenestration Rating Council's (NFRC) Procedure 100-91 (NFRC 1991). Because the HUD standard does not currently reference NFRC's rating procedure or lists of U-values, window performance remains more uncertain in the manufactured home industry. Manufacturers rely in many cases on AAMA tests, the results of which often differ from the NFRC values or ASHRAE defaults. This is particularly the case with the prime and storm window combination, where the difference between ASHRAE default values and AAMA tests is especially striking. Where possible, the NFRC U-values were used in the study. If an installed product was not found in the NFRC's Certified Products Guide (NFRC 1995), its U-value was calculated based on ASHRAE default values and procedures (Table 3-2).

Table 3-2 **Window assembly description and performance**

Window Description	**U-value (Btu/hr °F ft^2)**	**U-value source**
Single glazing, aluminum frame*, interior storm window (at least 3.5 inch space between prime & storm window)	***0.70***	1985 ASHRAE *Fundamentals*, Chapter 27, Table 13, Parts A & C
Double glazing, aluminum frame	***0.80***	1985 ASHRAE *Fundamentals*, Chapter 27, Table 13, Parts A & C
Double glazing, vinyl frame w/ alum. reinforcement	***0.52***	NFRC (January, 1995)
Double glazing, vinyl frame	***0.50***	NFRC (January, 1995)
Double glazing, vinyl frame, alum. reinforcement, hard coat low-e	***0.42***	NFRC (January, 1995)

* None of the aluminum frame assemblies in this table have a spacer with a thermal break.

The U-values for other components were easier to determine. Dataplate R-values or U-values were recorded on the audit sheets and were the starting point for U-value determination. This information was supplemented with calls and in-plant visits to some of the manufacturers whose homes were studied. The field researchers noted the condition of the bottom board, register boots, and other notable details which could contribute to efficiency losses. These descriptions can be found in the protocol sheets.

Standardized parallel heat flow techniques (as described in detail in standard references such as ASHRAE *Fundamentals*) were employed to find the U-values. In the case of the floor, the U-values are based on previous calculations that account for insulation compression and thermal shorts (Davis and Baylon 1992). A U-value of 0.050 was used for homes with R-22 underfloor blankets, the most commonly specified nominal floor insulation strategy among the homes in the study. In all cases, the crossover ducts had a nominal R-value of 4.2, the minimum level of thermal protection required under the HUD standards.

Table 3-3 lists duct system insulation levels. Information about the duct construction was reported by field technicians and verified through review of the manufacturer's installation specifications. Only two of the homes in North Carolina have fiberglass insulation wrapped around the underfloor ducts and in one case the insulation is not continuous over the surface of the duct. All the underfloor ducts in the New York homes are uninsulated. Perimeter distribution systems were installed in some of the homes. In North Carolina, the connections between the trunk duct and risers (register take-off) are taped from above. In most of the New York cases, the trunk to boot connections are taped before the entire assembly is placed in the floor. One of the New York cases (NY-6) has trunks constructed of fiberglass duct board and flex duct for the branches.

Table 3-3 **Duct characteristics**

Home ID	**Trunk duct material**	**Trunk duct nominal R-value**	**Branch duct material**
NC-1	sheet metal	uninsulated	flex duct
NC-2	sheet metal	uninsulated	n/a
NC-3	sheet metal	uninsulated†	flex duct
NC-4	sheet metal	uninsulated	n/a
NC-5	sheet metal	7	n/a
NC-6	sheet metal	uninsulated	n/a
NC-7	sheet metal	uninsulated	n/a
NC-8	sheet metal	uninsulated	flex duct
NY-1	sheet metal	uninsulated	n/a
NY-2	sheet metal	uninsulated	flex duct
NY-3	sheet metal	uninsulated	n/a
NY-4	sheet metal	uninsulated	n/a
NY-5	sheet metal	uninsulated	n/a
NY-6	duct board	3.5	flex duct

† Trunk duct is only partially wrapped with batt insulation and assumed in the modeling to thermodynamically behave like an uninsulated duct.

Notes: All cases have R-22 underfloor insulation and R-4.2 flex crossover duct. Sheet metal is flat stock 26 gauge aluminum which is fabricated in-plant. All cross-over ducts have an insulation R-value of 4.2.

3.3.4. Air leakage, air handler, and supply register data

Blower door and Duct Blaster ™ tests were performed on all homes in order to quantify leakage through the building shell and the duct system. Results of the house air leakage tests are presented in Table 3-4. All blower door leakage measurements were corrected for altitude and adjusted to standard reference temperature. The result is expressed in units of standard cubic feet per minute (SCFM). Average and median values are reported for North Carolina and New York, as well as the combined average and median. Since the number of test cases is small, the overall averages are better indicators of house tightness than comparisons between results from the two states. The average blower door tightness measurement at 50 pascals (ACH $_{50}$) is 11.0 air changes per hour (ACH). The median value is 10.8 ACH.

The blower door does not measure a home's natural infiltration/exfiltration rate, but rather its tightness at various pressure differentials, such as 50 pascals. Mathematical estimation is necessary to predict natural infiltration/exfiltration, which is due to the combination of stack (buoyancy) effect and wind effects. In the past decade, the rule-of-thumb for converting ACH_{50} to ACH_{nat} has been to divide ACH_{50} by about 20. This approach was confirmed by Kronvall and Persily in 1982 and refined by Lawrence Berkeley Laboratory.

The divide-by-20 rule was originally applied to site-built homes, which generally have two stories and a different pattern of high and low leaks than many manufactured homes. In a similar fashion, perfluorocarbon testing was used in a study of manufactured homes (Palmiter, et al. 1992) yielding a divisor that converts measured tightness into natural infiltration estimates as a function of local climate and average wind speed. The Raleigh, NC, climate is relatively mild and calm, so the estimated ACH_{nat} is found by dividing ACH_{50} by 27. Upstate New York is colder, with a more pronounced stack effect during the heating season, so for these cases ACH_{50} is divided by 24 to estimate ACH_{nat}.

Normally, the results from the tracer gas tests would be converted to natural infiltration rates. However, tracer gas results can be quite variable because of the conditions under which the tests are performed. In a majority of cases, the decay tests were performed during the middle of the day, when the main natural infiltration/exfiltration driving force (difference in temperature between inside and outside the home) was minimized. In addition, there was a reintroduction of tracer gas to the living spaces of the homes from the underfloor area that biases the decay results. These factors partly account for the relatively low natural decay rate.

The range of air leakage values among the homes in the study when estimated by the tracer gas measurement method is quite large, epitomizing the difficulties associated with a small sample size. The overall average tracer gas air-change rate with the furnace fan turned off is 0.35 ACH, coincidentally agreeing with the target total infiltration rate required by the HUD standards and recommended by ASHRAE in Standard 62-89 (ASHRAE 1989). The average tracer gas air change rate with the furnace fan on is 0.46 ACH. The average of the differences between the tests with the fan on and off is 0.11 ACH.

The range between the fan-on and fan-off tracer decay values is substantial. For NY-6, the decay rate measured with fan on is actually 0.03 ACH *less* than with the fan off, and for NC-3, the ACH with the air handler fan on is 0.32 ACH greater than the decay rate with the fan off. The expected result would be for the decay rate to be much higher when the fan is on rather than off; this would be consistent with results found by other researchers.

On average, the homes' air leakage rate, as estimated from the blower door tightness results, is roughly in line with the total infiltration rate specified by the HUD standard. The data from three of the New York homes were collected at the retail lot. In these instances, the marriage line was not permanently sealed. This may partially account for the fact that their measured air leakage levels are noticeably higher than the site-installed North Carolina homes. Two New York homes (NY-3 and NY-5) were originally tested on the retail lot, then moved and retested. In these cases, the blower door tests were repeated and the figures on the table correspond to the homes after site setup.

Table 3-4 **Air leakage and pressure diagnostic data**

Home ID	Blower door flow (SCFM$_{50}$)[1]	Air changes per hour (ACH$_{50}$)	Natural air changes per hour[2]	Tracer gas decay results			ΔP Measurement[3]	
				Fan Off ach	Fan On ach	Difference ach	Fan On (pascals)	Across bedroom door (pascals)
NC-1	2232	8.7	0.32	0.29	0.25	-0.04	-0.8	n/a
NC-2	1781	10.6	0.39	0.31	0.46	0.15	-1.2	7.5
NC-3	2212	8.6	0.32	0.31	0.63	0.32	-0.2	3.3
NC-4	1498	13.1	0.49	0.49	0.56	0.07	n/a	3.2
NC-5	2120	9.4	0.35	0.27	0.29	0.02	-0.6	1.4
NC-6	1685	8.2	0.30	0.25	0.29	0.04	-1.6	4.7
NC-7	2966	15.1	0.56	0.42	0.73	0.31	-0.4	3.8
NC-8	2288	7.7	0.29	0.26	0.44	0.18	-0.6	n/a
NY-1	2547	10.9	0.52	0.36	0.39	0.03	-0.2	n/a
NY-2	2712	12.0	0.57	0.29	0.43	0.14	-0.1	1.2
NY-3	2194	15.3	0.73	0.54	0.62	0.08	-1.6	4.5
NY-4	1387	9.7	0.46	0.70	0.73	0.03	-2.1	3.9
NY-5	2288	12.9	0.61	0.12	0.40	0.28	-0.3	3.0
NY-6	2513	11.4	0.54	0.32	0.29	-0.03	0.0	2.8
North Carolina								
Average	2098	10.2	0.38	0.33	0.46	0.13	-0.8	4.0
Median	2166	9.0	0.33	0.30	0.45	0.11	-0.6	3.6
Std. Dev.	456	2.6	0.10	0.09	0.17	0.13	0.5	2.0
New York								
Average	2274	12.0	0.57	0.39	0.48	0.09	-0.7	3.1
Median	2401	11.7	0.56	0.34	0.41	0.06	-0.3	3.0
Std. Dev.	473	1.9	0.09	0.20	0.16	0.11	0.9	1.3
All homes								
Average	**2173**	**11.0**	**0.46**	**0.35**	**0.46**	**0.11**	**-0.8**	**3.6**
Median	**2222**	**10.8**	**0.47**	**0.31**	**0.44**	**0.08**	**-0.6**	**3.3**
Std. Dev.	**454**	**2.5**	**0.14**	**0.14**	**0.16**	**0.12**	**0.7**	**1.7**

[1] Raw data is corrected to standard temperature and pressure.

[2] ACH$_{50}$ divided by 24 in New York and 27 in North Carolina to estimate natural infiltration rate.

[3] The first measurement is the pressure across the house envelope (reference outside) when the air handler fan is turned on. The second measurement is the highest pressure measured across a closed bedroom door when the air handler fan is running.

Two pressure readings are reported in Table 3-4: overall envelope pressure when the air handler fan is on, and the highest pressure measured across a bedroom door (with respect to the home's interior) when the air handler is on. In all but one instance, the home was depressurized by the operation of the furnace fan. This effect was expected, given the absence of a ducted return in manufactured homes. Pressurizing or depressurizing the home during air handler operation results in an increase in infiltration of outside unconditioned air, increasing the load on the HVAC equipment. This translates into a reduction in overall system efficiency.

Field researchers also measured the differential pressurization caused by the closing of interior doors. The highest pressure across a bedroom door is reported in the table. Previous researchers (e.g., Tooley and Moyer 1989) have noted large pressure differentials caused by interior door closures. The equipment is starved for return air and the result is an increase in outside air infiltration into the spaces closest to the return grille. In manufactured homes, this effect can be heightened because of small room size, inadequate door undercuts or over-door return grilles and (in many cases) relatively large supply register flows which overpressurize small bedrooms. The precise nature of these pressure differentials as related to design and operation (and their impact on air infiltration and interior air flows) was not explored in this work but warrants further study.

Additional pressure diagnostics were performed to check the integrity of the bottom board, an air and moisture barrier attached to the underside of the home. The test, conducted only on units in North Carolina, was performed with the home and supply system depressurized to 50 pascals with respect to outside. A pressure probe was inserted through small holes around register boots to measure the pressure in the floor cavity relative to the house. A small pressure differential indicates that the bottom board is acting as an effective air barrier. Large positive pressure readings indicate the blower door is pulling in significant amounts of outside air through holes in the bottom board, pressurizing the underfloor zone relative to the inside of the home. The underfloor pressure with respect to the house was measured in two registers, one in each of the two trunk runs (sides “A” (furnace side) and “B” of the multi-section homes). Results are displayed on Table 3-5.

Table 3-5 **Series pressure measurement**

Home ID	**Pressure measurement (pascals)***		
	Side A	**Side B**	**Average A and B**
NC-1	*24*	*27*	*25.5*
NC-2	*26*	*27*	*26.5*
NC-2 **	*8*	*18*	*13*
NC-3	*13*	*35*	*24*
NC-4	*n/a*	*n/a*	*n/a*
NC-5	*27*	*45*	*36*
NC-6	*42*	*47*	*44.5*
NC-7	*40*	*24*	*32*
NC-8	*n/a*	*n/a*	*n/a*
Average	***26***	***32***	***29***

* Measurements taken with interstitial space as input channel and the home depressurized to 50 pascals with respect to the exterior.

** Post repair measurement

With the home depressurized to 50 pascals, the average floor cavity pressure measurement for the North Carolina homes was 29 pascals, suggesting that air in the underfloor zone has as easier path to the exterior than to the living space.

The bottom board is not particularly effective in redirecting air leaked from ducts back into the house. The efficacy of securing the bottom board is evident from the NC-2 site results. Repairs were made to the bottom board of this home, significantly increasing its effectiveness as an air barrier, as reflected in the lower series pressure measurement.

A pressure pan test was performed on all registers in all homes (results are displayed on Table 3-6). The test was also performed with the blower door running and the house depressurized to 50 pascals. The pressure pan offers a semi-quantitative assessment of duct leakage. The pan readings depend on the size and location of duct leaks relative to the position of the pan. A very large leak adjacent to the pan will produce a relatively high reading.

Table 3-6 **Pressure pan measurements**

Home ID	Maximum pressure (pascals)	Average pressure (pascals)	Number of registers with readings over 2 pascals	Total number of registers
NC-1	*5.4*	*1.6*	*4*	*14*
NC-2	*2.0*	*1.3*	*0*	*9*
NC-3	*n/a*	*n/a*	*n/a*	*n/a*
NC-4	*1.9*	*1.0*	*0*	*9*
NC-5	*1.8*	*0.8*	*1*	*11*
NC-6	*4.5*	*1.0*	*1*	*11*
NC-7	*2.7*	*1.4*	*1*	*13*
NC-8	*3.7*	*2.0*	*6*	*13*
NY-1	*0.8*	*0.6*	*0*	*14*
NY-2	*2.6*	*1.5*	*1*	*14*
NY-3	*0.6*	*0.3*	*0*	*8*
NY-4	*0.6*	*0.4*	*0*	*9*
NY-5	*1.2*	*1.1*	*4*	*8*
NY-6	*13.3*	*3.0*	*5*	*12*

Note: Home at 50 pascals with respect to the exterior.

A commonly used rule-of-thumb (as suggested by John Tooley of AEC) is to consider a register and boot sufficiently sealed if the pressure pan reading is less than 2 pascals. Most homes had at least one register with a pan reading above 2 pascals. Given the short useful life of many commonly used duct sealing materials (one to two years), pressure pan readings can be expected to increase within a few years of original occupancy. (Register-by-register pressure pan results are listed in the appendix.)

Duct leakage data are shown in Table 3-7. In determining exterior duct leakage, the field crews employed the approach detailed in the Minneapolis Duct Blaster ™ manual (The Energy Conservatory 1993). The duct system was sealed off from the home and pressurized (or depressurized) to two reference pressures (25 and 50 pascals with respect to outside of the home), as measured with a static pressure probe in the sealed duct system. The blower door was turned on and adjusted to equalize the pressure between the house and the underfloor area. The pressure in the duct system was readjusted to the desired value. The amount of air then flowing through the Duct Blaster ™ at each reference pressure is an estimate of the exterior duct leakage.

The average exterior duct leakage for these homes at 25 pascals is 171 standard cubic feet per minute (SCFM). When this leakage is normalized by the lineal feet of ductwork in the home, a better comparative measure of duct tightness, the average is 1.34 SCFM per foot of ductwork. The range of values is from 0.47 SCFM per foot at NC-1 to 2.93 SCFM per foot at NC-2. On average, the New York homes have less leakage per foot of duct run. This is not unexpected, given that the manufacturer of four of the six New York homes fabricates and seals the ducts prior to installation in the home. The duct systems installed in the North Carolina homes were sealed after the assembly of the floor and could only be taped on the inside of the duct work. The latter assembly sequence is much more common.

The field crew measured the static pressure in the duct system during normal furnace operation. This measurement was taken with a Pitot tube placed in the trunk duct below the supply register closest to the furnace. The duct static pressure is not measured in the furnace plenum because of difficulties accessing this area and possible inaccuracies in measurements due to localized pressure effects (i.e., eddies).

To find a system-wide reference pressure, the measured static pressure is then multiplied by 0.8, a factor that takes into account differences in duct pressure across the entire duct system. This system-wide pressure is the average driving force pushing heated air out of the ducts and into the interstitial space above the underfloor insulation. Because they do not have a true supply plenum as found in site-built construction, manufactured housing duct systems often maintain a consistent pressure between the duct region near the air handler fan and the duct region at the far end of the home. That is, the static pressure drop is often relatively small between the outlet from the air handler fan and the supply boot at the end of the duct run. In site-built duct systems, a multiplier of 0.5 is generally used to estimate system-wide static pressure. This modifier assumes the average static pressure in the duct system is halfway between the static pressure measured at (or near) the supply plenum and the static pressure measured in a supply register (usually near zero). Pending further research, the 0.8 multiplier for manufactured homes is a better estimate of the average duct system static pressure.

Table 3-7 **Duct leakage and air handler results**

Home ID	Exterior duct leakage at 25 pascals (SCFM)	Duct leakage at 25 pascals per foot of duct (SCFM)	Exterior duct leakage at 50 pascals (SCFM)	Duct pressure (pascals)	Reference duct pressure (80% measured pressure)	Calculated ext. duct leakage at reference pressure (SCFM)	Sum of register flows (SCFM)	Computed air handler flow (SCFM)*	Supply leakage fraction (%)
NC-1	90	0.47	132	12.5	10.0	48	790	838	5.7
NC-2	262	2.93	351	19.0	15.2	176	843	927	17.3
NC-3	157	0.96	235	6.2	5.0	54	808	862	6.2
NC-4	146	1.65	222	30.0	24.0	140	742	881	15.9
NC-5	139	1.48	215	20.0	16.0	103	1023	1126	9.2
NC-6	123	1.27	187	22.0	17.6	97	773	869	11.1
NC-7	283	2.40	394	10.0	8.0	127	676	803	15.8
NC-8	308	1.44	459	23.8	19.0	251	469	720	34.9
NY-1	158	0.71	229	11.0	8.8	77	740	817	9.4
NY-2	195	0.93	299	5.9	4.7	65	747	812	8.0
NY-3[†]	77	1.11	113	15.5	12.4	47	662	709	6.6
NY-4	91	0.89	137	31.2	25.0	89	749	838	10.7
NY-5	151	1.45	216	16.5	13.2	95	660	756	12.6
NY-6	216	1.09	336	23.7	19.0	180	707	887	20.3
North Carolina									
Average	188	1.58	274	17.9	14.4	124	765	878	14.5
Median.	151	1.46	229	19.5	15.6	115	781	866	13.5
Std. Dev..	83	0.78	113	7.9	6.3	67	157	117	9.4
New York									
Average	148	1.03	222	17.3	13.8	92	711	803	11.3
Median.	155	1.01	222	16.0	12.8	83	724	815	10.0
Std. Dev..	55	0.25	87	9.0	7.2	46	41	63	4.9
Combined Averages									
Average	**171**	**1.34**	**252**	**17.7**	**14.1**	**111**	**742**	**846**	**13.1**
Median.	**154**	**1.19**	**225**	**17.8**	**14.2**	**96**	**744**	**838**	**10.9**
Std. Dev..	**73**	**0.66**	**103**	**8.0**	**6.4**	**59**	**121**	**102**	**7.7**

[†] Single section home

* Sum of register flows and calculated exterior duct leakage

The exterior duct leakage is calculated by using the ratio of the 80 percent duct system static pressure to the exterior duct leakage measured at 25 pascals, raised to an assumed duct leakage flow exponent of 0.65. The conversion is based on the combined flow equation ($Q = C\ \Delta P^n$, where Q is the volumetric flow; C is the flow at 25 pascals, that is, $C = \text{Flow}_{25}/25^{0.65}$; ΔP is the pressure differential across a leak opening; *n* is a flow exponent which describes the characteristics of the opening, where n=0.50 for flow through a perfect orifice and n=1 for flow through a long, sharp-edged crack):

$$\text{Leakage (in cfm)} = (\text{exterior duct leakage at 25 Pa})\,(0.80(\text{measured duct static pressure})/25)^{0.65} \quad (\mathbf{1})$$

The next hurdle in the analysis was to come up with a reliable air handler flow. Determination of air handler flow is essential to describe the percentage of heated air (supply leakage fraction (SLF)) which is lost between the furnace and the home’s supply registers. Three field approaches were used to find the air handler flow. First, the temperature rise across the furnace was compared to the energy input at the furnace (as measured with clamp-on power meters in North Carolina or pulse input meters in New York.) This technique can be unreliable because of difficulties in obtaining accurate supply plenum temperatures and incomplete mixing of air in the supply plenum (the latter is especially a problem in manufactured homes that typically lack a standard HVAC plenum). As a result, the air handler flows estimated by the temperature rise method in these homes are unusable in many instances.

The second field test for finding air handler flow is to close off the furnace cabinet, leaving an opening large enough to admit the Duct Blaster ™ and then use the Duct Blaster™ to supply all air to the furnace during normal heating operation. This method too often produces unreliable results, but it was conducted for purposes of double-checking the collected data. Unfortunately, the results from this test were also unreliable for purposes of calculating a supply leakage fraction.

The third method used to estimate the air handler flow is to add the sum of the supply register flows to the calculated exterior duct leakage. Supply register flow was measured using a Duct Blaster ™ for homes in North Carolina and the Pacific Science and Technology *Fast-1* flow hood for the New York sample. The supply leakage fraction (last column of Table 3-7) is calculated by dividing the computed exterior duct leakage by the air handler flow. This final method proved to be the most reliable measure of air handler flow, and was used for most of the analyses.

3.4. Efficiency analysis and results for new HUD-code homes

This section of the report presents the analysis results including system efficiencies. Empirical estimates of steady-state heat delivery efficiency are compared with modeled steady-state heat delivery efficiency. In the next section, results from the coheat tests of homes in Northwest are presented, and the overall system efficiency (which includes cycling losses and recovered heat) is calculated for the HUD-code homes by using the average heat recovery factor derived from the coheat analysis. The heat recovery efficiency is that portion of the heating energy that reaches the living spaces either by thermosiphon from ducts after the furnace turns off or by means of heat transfer through the floor system. This is heat reclaimed from the conductive and leakage duct losses. Testing for the heat recovery factor was beyond the scope of the present study. Therefore, the proportion of heat recovered for the HUD-code homes is based on prior tests of MAP homes.

Applying the MAP factors probably overestimates the real performance of the HUD-code homes (that is, the lower insulation levels in these units, when compared with the MAP homes, will translate into lower relative recovery efficiency). Other factors may have led to optimistic projections of heat delivery efficiency in the HUD-code homes. For example, the homes were tested shortly after manufacture, so air seals had not had much time to fail. Further, the tests were conducted with all interior doors open, minimizing problems associated with differential pressurization among the major living spaces of the home.

3.4.1. Heat delivery efficiency testing and analysis procedure

The testing procedure was straightforward. Thermistor temperature probes were placed in the supply plenum, the return plenum, adjacent to the thermostat, outside the home, and in the interstitial duct zone between the underfloor insulation and the subfloor. Four probes were placed in the underfloor zone: two were placed adjacent to the trunk ducts and two were placed in the outrigger region. Temperatures were recorded automatically every minute. The thermostat was set at about 70 ° F and the furnace operated for at least ten minutes. At this point, field technicians measured flows from the supply registers and also recorded delivery temperatures as measured with a hand-held thermocouple thermometer.

The heat delivery efficiency, as defined by ASHRAE in Chapter 29 of the 1992 *HVAC Systems and Equipment Handbook,* is the ratio of the total useful heat delivered to the supply registers while the fan is on, divided by the power input to the furnace. The energy from the air handler fan is included in the power input to the furnace. The air handler power was measured with the clamp-on meters in North Carolina and pulse meters for gas or propane-heated homes in New York. Because the air handler power was not measured in the New York homes, a default value of 400 watts was used for these homes.

The protocol used for the field testing of the fourteen HUD-code homes calls for measurements of register flow and register temperature to be made after the furnace has been operating for at least ten minutes. At this point, it is assumed that the ducts, duct insulation, and surrounding floor structure have been heated to near their maximum temperature, and the measurements are then taken. As the test progresses, it is assumed that the register supply temperatures do not change appreciably; although the air temperature in the home is apt to continue to rise.

In fact, the distribution system rarely (if ever) reaches a true steady-state condition. Even after fifteen or twenty minutes, small increases in register temperatures can be observed. Since register temperatures were not monitored continuously during these tests (due to the limitations of the measuring devices) the difference between actual conditions and true steady-state could not be ascertained. In some homes, the auditors returned to the registers after the initial measurements and noted a second register delivery temperature. When this was done, an average of the readings was assumed to be the representative register delivery temperature. If the system has not completely warmed up when register flow and temperature are measured, the overall effect is to underestimate steady-state efficiency. In general, fossil-fuel fired furnaces reach the steady-state phase more quickly than electric furnaces since they burn much hotter than electric furnaces. However, as the exact energy content of the fossil fuel is unknown, the New York pulse meter readings may be subject to some error.

To actually calculate the heat delivery efficiency, the volumetric register flows are combined with the temperatures measured at the registers to calculate the instantaneous rate of energy delivery at each register. This instantaneous rate is then weighted by the measured register flow and summed, producing a value for total instantaneous energy delivery to the home's interior. This value is then divided by the energy input into the furnace (as measured by clamp-on power meters or the pulse input meter). In the fossil-fuel cases, the input energy is modified by the combustion efficiency of the furnace (as specified by the Gas Appliance Manufacturers Association), and the resulting quotient is taken as the steady-state heat delivery efficiency.

3.4.2. Measured efficiency results

Table 3-8 shows the empirically-determined steady-state heat delivery efficiency for the HUD-code homes. There is a considerable variation from house to house. The median value from the two states is 61 percent. The results for the North Carolina homes display less variability than the corresponding figures for the homes in New York. The standard deviation of the heat delivery measurement in North Carolina is 6 percent of the mean, whereas in New York it is nearly 30 percent of the mean. (Note: NC-8, a modular unit constructed similarly, though not identical to, a HUD-code manufactured home, was excluded from the analysis.)

The relatively low measured efficiencies in some cases are probably due in part to incomplete warm-up of the floor system and ducts. Conductive losses could still have been increasing when temperature and flow measurements were taken.

In the case of NY-3, the relatively high heat delivery efficiency measurement might be partly due to the very modest exterior duct losses. This is a single section home lacking a crossover duct. New York's average measured steady state heat delivery efficiency, even correcting for combustion losses, is slightly higher than average for North Carolina homes. This is probably due in part to the hotter burn temperature of the New York furnaces. In some cases, the maximum supply plenum temperature measured in New York furnaces exceeded 150 ° F.

Table 3-8 **Steady-state heat delivery efficiency measurements**

Home ID	**ΔT across furnace (°F)**	**Supply register power * (watts)**	**Furnace power (watts)[†]**	**Steady-state Heat Delivery Efficiency (%)**
NC-1	*64.0*	*8,704*	*14,500*	*60*
NC-2	*49.0*	*1,2431*	*17,550*	*71*
NC-3	*58.9*	*10,325*	*17,050*	*61*
NC-4	*52.9*	*8,956*	*15,290*	*59*
NC-5	*46.5*	*9,823*	*16,100*	*61*
NC-6	*55.7*	*13,041*	*19,500*	*67*
NC-7	*51.6*	*9,698*	*15,760*	*62*
NY-1	*95.2*	*8,746*	*21,040*	*42*
NY-2	*89.2*	*11,853*	*15,280*	*78*
NY-3	*76.8*	*12,977*	*13,845*	*94*
NY-4	*61.4*	*10,561*	*15,104*	*70*
NY-5	*77.6*	*9,004*	*17,327*	*52*
NY-6	*62.6*	*8,956*	*18,590*	*48*
North Carolina				
Average	*54.1*	*10425*	*16536*	*63*
Median	*52.9*	*9823*	*16100*	*61*
Std. Deviation	*6.0*	*1678*	*1662*	*4*
New York				
Average	*73.5*	*10,670*	*1,6864*	*64*
Median	*77.2*	*9,782*	*16,304*	*61*
Std. Deviation	*13.6*	*1,763*	*2,659*	*20*
Combined Averages				
Average	***64.7***	***10,390***	***16,687***	***63***
Median	***61.4***	***9,823***	***16,100***	***61***
Std. Deviation	***15.4***	***1,644***	***2,087***	***13***

* Flow-weighted sum of supply registers

[†] In New York, Btu/hr readings are converted into watts. Furnace input energy is New York is corrected for the GAMA-listed AFUE.

3.4.3. Heat delivery efficiency modeling

Given the small sample size and relatively large standard deviation, a second method for predicting heat delivery efficiency was employed. The method is based on a mathematical model that estimates steady-state heat delivery efficiency using principles of mass flow, heat balance, and fluid dynamics. A paper describing the form currently in use (Palmiter and Francisco 1995) was presented at the 1995 ASHRAE spring conference. During the last few years, the model has been calibrated repeatedly with detailed data from short-term coheat tests.

The model includes factors for duct conduction losses, duct air leakage, and a factor which accounts for the interaction of the air handler fan with the home's natural infiltration rate. The model's consolidated form, without the mechanical/natural infiltration interaction factor, is shown below (2). Although there is no ducted return system, the middle term is included for completeness.

$$e = a_s b_s - a_s b_s (1 - a_r b_r) \frac{\Delta T_r}{\Delta T_e} - a_s (1 - b_s) \frac{\Delta T_s}{\Delta T_e} \quad \textbf{(2)}$$

where:

e = overall distribution efficiency of the heating system
a_s = air leakage efficiency of the supply ducts, equal to (1 - (supply leakage fraction))
b_s = conductive efficiency of the supply ducts, found from physical measurements of the duct system and observed or inferred R-values of duct insulation
a_r = air leakage efficiency of the return ducts (if present)
b_r = conductive efficiency of the return ducts (if present)
DT_r = the temperature difference (in ºF) between the home's interior and the temperature of the air around the return duct (if present)
DT_s = the temperature difference (in ºF) between the home's interior and the underfloor (interstitial) space during the steady-state heat delivery efficiency measurement
DT_e = the temperature rise across the furnace during the steady-state heat delivery efficiency measurement

Removing the term for the return system, the resulting equation is as follows:

$$e = a_s b_s - a_s (1 - b_s) \frac{\Delta T_s}{\Delta T_e} \quad \textbf{(3)}$$

The supply leakage fraction is calculated based on the Duct Blaster ™ measurement of exterior duct leakage (Table 3-7). The model assumes all air leaks occur at the end of duct runs instead of at the furnace. If it is assumed that all leaks occur at the air handler, the overall efficiency (ε) typically decreases by one to three percent.

The extra infiltration induced by air handler operation is determined from the difference between the fan-on and fan-off tracer gas decay rates. Although the absolute decays are suspect, the difference can be used to estimate the added leakage. The nominal infiltration is compared to the estimated natural infiltration rate (from the blower door test) to determine the combined natural/mechanical ventilation rate.

Modeled steady-state heat delivery efficiency is summarized in Table 3-9. The combined distribution of modeled results for both states has a slightly lower standard deviation (as a percentage of the mean) than the empirical results shown on Table 3-8. The combined average modeled efficiency from the two states is 62 percent with the combined median steady-state heat delivery efficiency 63 percent. The North Carolina homes have a higher predicted steady-state delivery efficiency than the New York homes despite the fact that the New York homes showed lower duct leakage. This is, in part, explained by the shorter average duct runs in the North Carolina homes (20 feet shorter on average) and the use of duct insulation in some of the branch runs. Only one home in this sample (NY-6) has insulated trunk ducts. Another home (NC-5) is modeled as having R-7 duct insulation determined by manufacturer practice and date of construction rather than field verification. The variance between the empirical and modeled estimates is higher for the New York homes -- possibly because the effective temperature for the interstitial space is harder to quantify for the higher temperature combustion-heated homes.

Table 3-9 **Modeled steady-state heat delivery efficiency results**

Home ID	**Modeled steady-state heat delivery efficiency (%)**
NC-1	*63*
NC-2	*58*
NC-3	*63*
NC-4	*61*
NC-5	*83*
NC-6	*67*
NC-7	*60*
NY-1	*48*
NY-2	*44*
NY-3	*70*
NY-4	*56*
NY-5	*56*
NY-6	*60*
North Carolina	
Average	*65*
Median	*63*
Std. deviation	*8*
New York	
Average	*56*
Median	*56*
Std. deviation	*9*
Combined Averages	
Average	***61***
Median	***60***
Std. deviation	***10***

3.5. Results from the Northwest and recasting of the efficiency estimates

In the early spring of 1994, short-term coheat tests were conducted on six manufactured homes situated in the Pacific Northwest and built to Model Conservation Standards sponsored by local electrical utilities and the Bonneville Power Administration. The detailed results of the field testing are found in Davis et al. (1994). Three more homes were tested in early 1995. Manufacturers were given a cash incentive to build electrically-heated manufactured homes to specifications which produced homes with a U_o-value of 0.053 Btu/hr °F ft^2. The program ended in late July 1995 with about 50,000 homes included in the program .

The homes which were tested displayed very low levels of duct leakage. In addition, conductive duct losses were expected to be limited because MAP specifications require R-33 underfloor insulation and R-5 duct wrap. A summary of physical characteristics and air leakage results is found in Table 3-10.

Table 3-10 **Physical data from MAP coheat homes**

House ID	Width class	Floor area (ft^2)	Underfloor/ duct insulation R-value	Blower door ACH$_{50}$	Exterior duct leakage at 25 pascals per ft of ductwork (SCFM/ft)	Exterior duct leakage at 80% ref. pressure (SCFM)	Supply leakage fraction (%)
MAP-1	Double	960	33/5	4.00	0.41	23.1	3.1
MAP-2	Double	1716	33/5	5.17	0.64	64.4	8.3
MAP-3	Triple	2038	33/5	3.20	0.66	91.8	8.8
MAP-4	Double	1709	33/5	3.40	0.16	20.5	2.1
MAP-5	Double	1699	33/5	3.25	0.47	60.9	8.9
MAP-6	Double	1739	33/5	4.23	0.40	46.6	7.2
MAP-7	Double	1340	33/5	5.50	0.55	36.7	3.9
MAP-9	Single	846	33/5	7.50	0.85	42.6	4.9
Average		**1506**		**4.53**	**0.52**	**48.3**	**5.9**
Median		**1704**		**4.12**	**0.51**	**44.6**	**6.1**
Std. Deviation		**418**		**1.47**	**0.21**	**23.6**	**2.7**

The coheat procedure is designed to collect enough information in an overnight test to provide estimates of steady-state heat delivery efficiency, cycling heat delivery efficiency, and overall system efficiency. Another measure, the heat recovery efficiency, is calculated from the system efficiency and the cycling heat delivery efficiency. The heat recovery efficiency is that portion of the heat which is not delivered to the home’s interior by the heating system’s air stream but is recovered when the furnace fan turns off. The cycling heat delivery efficiency differs from the system efficiency in that it does not include heat recovered from supply leaks back into the home, heat recovered from the ducts during the furnace off-cycle, or heat recovered from buffer zones or the floor’s structural members. Therefore, the cycling efficiency is always expected to be lower than the system and steady-state heat delivery efficiency.

The system efficiency is the figure of merit in coheat analysis. The system efficiency is defined as the total useful heat delivered to the conditioned space during the entire furnace cycling time, divided by the power input to the furnace. System efficiency takes into account any supply leaks back into the home, plus any heat recovered by the living space when the furnace fan is off. The system efficiency's "total useful heat" refers to the power that the same home would use if equipped with electric baseboard heaters (with ducts in place and open to the conditioned space, but with the furnace off) and maintaining the same average indoor temperatures as those provided by the furnace during normal cycling.

The short-term coheat protocol replaces these theoretical baseboard heaters with 800/1500 watt portable heaters. A software algorithm directs relays to turn the heaters on and off, maintaining room-by-room temperatures within a very close margin of the average temperatures measured during furnace cycling. The furnace and portable coheaters are alternated on two-hour cycles. Electrical usage during these periods is measured by true power meters attached to the home's electrical main circuits. Room and supply register temperatures are measured with Type T thermocouple wires, and data is periodically downloaded from multi-channel dataloggers into the computer.

Generally, average power usage for the second hour of the coheat test is compared to the corresponding second hour power usage from the furnace test to estimate system efficiency. Steady-state heat delivery efficiency is calculated from the data collected during a time when the furnace has had an opportunity to warm-up for at least ten minutes.

The steady-state heat delivery efficiency is recorded in Table 3-11. This is the same parameter measured in the HUD-code homes. The steady-state heat delivery efficiency is measured after the whole distribution system is assumed to be "warmed up."

Table 3-11 also reports the cycling heat delivery efficiency, defined as the heat delivered to the home through supply registers during the time the air handler is running divided by the energy output of the heating system. This efficiency differs from the steady-state heat delivery efficiency in that it includes the warm-up period of furnace cycling as well as the plateau phase.

Table 3-11 **Efficiency results from MAP coheat test homes**

House ID	**Steady-state heat delivery efficiency (%)**	**Cycling heat delivery efficiency (%)**	**Heat recovery efficiency (%)**	**System efficiency (%)**
MAP-1	*85*	*64*	*53*	*83*
MAP-2	*80*	*74*	*58*	*89*
MAP-3	*88*	*67*	*42*	*81*
MAP-4	*89*	*85*	*14*	*87*
MAP-5	*73*	*61*	*34*	*74*
MAP-6	*80*	*71*	*73*	*92*
MAP-7	*79*	*67*	*34*	*78*
MAP-9	*85*	*76*	*75*	*89*
Average	***82***	***69***	***45***	***84***
Median	***83***	***67***	***47***	***85***
Std. Deviation	***6***	***6***	***18***	***8***

The testing of the HUD-code homes was useful in identifying the steady-state heat delivery efficiency. However, the more relevant indicator of performance is system efficiency, a value that can be related to seasonal energy use. To derive the system efficiency for the HUD-code homes, the simplifying assumption was made that the cycling heat delivery efficiency and heat recovery percentage for these homes matches the MAP homes. That is, the off-cycle losses and off-cycle heat recovery measured as part of the MAP coheat study were applied in computing HUD-code home system performance. This is a useful approximation method, although given the relatively superior thermal levels (i.e., lower conductive losses) and lower duct leakage that characterized the MAP homes, this approach tends to overstate the system efficiency of the HUD-code homes.

To derive the system efficiency, the following equation is applied to median values from the HUD-code and MAP home data set:

$$E_{SYS} = E_{SS\text{-}HUD} [1 - (1 - (E_{CYC}/E_{SS\text{-}MAP}))E_{HR}] \quad \textbf{(4)}$$

where:

E_{SYS} = the calculated system efficiency for HUD-code homes
$E_{SS\text{-}HUD}$ = the steady-state heat delivery efficiency from HUD-code data
$E_{SS\text{-}MAP}$ = the steady-state heat delivery efficiency from MAP coheat tests
E_{CYC} = the cycling heat delivery efficiency (from MAP coheat data)
E_{HR} = the heat recovery percentage (from MAP coheat data)

Applying this equation to the median MAP cycling steady-state heat delivery efficiency and heat recovery figures yields a value of 0.91 for the variables inside the square brackets. This multiplier is used to estimate HUD-code home heating system efficiency.

The summary statistics for measured and modeled steady-state heat delivery efficiency for the North Carolina and New York homes are shown in Table 3-12 below.

Table 3-12 **Steady-state heat delivery efficiencies for HUD-code homes**

	North Carolina (%)	**New York (%)**	**Both states (%)**
Average empirical	*63*	*64*	*63*
Median empirical	*61*	*61*	*61*
Average modeled	*65*	*56*	*61*
Median modeled	*63*	*56*	*60*

As stated above, because this calculation is based on the efficiencies and heat recovery percentages of homes built to higher thermal standards than the HUD-code homes in this study, the result should be viewed as a best-case estimate of expected system efficiency. The average of the combined median values for the modeled (63 percent) and measured (61 percent) steady-state heat delivery efficiency is 62 percent. When this value is multiplied by the system efficiency factor derived from the MAP home study of 0.91, the resulting estimated HUD-code system efficiency is 56 percent.

The Palmiter model can be used to predict the relative size of conduction and convection losses for three different loss categories: conduction, leakage, and air infiltration. The model explicitly accounts for the interaction between the energy delivered by equipment, the air leakage between the plenum and the registers, and the conductive losses in the duct. However, the model does not separate losses by source. A simplified parametric approach was taken to estimate the conductive and convective loss components. Air leakage was zeroed out and conductive losses estimated, then the combined algorithm was used to find overall losses. The convective loss was inferred as the difference between the total loss and the conductive loss. Mechanically-induced infiltration is calculated separately. The results are shown on Table 3-13.

Table 3-13 **Estimates of system efficiency losses by source***

Loss source	**MAP homes (%)**	**HUD-code homes with R-7 duct insulation (%)**	**HUD-code without duct insulation (%)**
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***

* The values on this table are based on a 1400 square foot home with an electric heating system with an 850 cfm blower, 120 ft of 4 inch x 10 inch sheet metal ductwork, and a supply leakage fraction of 10 percent for new HUD-code homes and 5 percent for MAP homes. These values are very close to the median values for the new-HUD-code homes in this study.

The model was designed primarily to estimate steady-state heat delivery efficiency. The same multiplier (0.91) employed in the conversion from steady-state heat delivery efficiency to system efficiency was applied to the model results to estimate system efficiency.

To derive the estimated system efficiency the total loss rate is subtracted from 100. Note the overall loss rate for the HUD-code homes with duct insulation is considerably less than HUD-code units manufactured with uninsulated sheet metal ducts. This is true even though the same supply leakage fraction (10 percent) is used for each HUD-code case. As manufacturing practices evolve toward the use of insulation to wrap the interior ducts, the conduction losses will drop dramatically. In the cost effectiveness analysis below, this trend is reflected in a “rounding up” of the system efficiency from the 56 percent estimated for the small sample of homes in this study to a conservative 60 percent that is perhaps a better indicator of current industry practice.

3.6. Cost-effectiveness of the MAP guidelines

Despite the limited ability to generalize from a small sample of homes, the results are a strong indication that homes built to the MAP guidelines will consistently outperform typical HUD-code construction. The MAP homes have insulation levels of R-33 in the underfloor area and R-5 wrapped around the sheet metal ducts. Typically, the HUD-code cases have R-22 underfloor insulation and uninsulated trunk ducts. In one case, the trunk duct is wrapped with an R-7 batt. All MAP homes have an R-8 crossover duct and the HUD-code homes have an R-4.2 crossover duct.

Based on the study results, the MAP requirements were subjected to a cost-benefit analysis comparing the average system performance of these homes with the HUD-code units. The results as reported below suggest that more rigorous building practices are cost justified. However, these results should be viewed with caution. For example, the MAP requirements were evaluated as a group and no attempt was made to isolate those aspects that are the most cost effective from those measures whose benefits might be marginal. In addition, the performance indicators(such as system efficiency) are subject to variability because of such factors as small sample size, differences in testing protocols, and regional variations in climate and construction practice. Nor is it likely that the MAP requirements include all or most of the cost-effective methods for reducing ADS-related energy use. Nonetheless, the results are instructive and suggest that opportunities exist for improving ADS performance and improve affordability.

The analysis was limited to two climates, Raleigh, NC, and Syracuse, NY. Simulation of energy use was based on the SUNDAY software, a program approved for use in the MAP program and benchmarked against other simulation programs and submetered data. Climate data was read from 30-year Typical Meteorological Year (TMY) tapes. The simulations are run on a prototype home to establish a base annual energy load. The extra energy required to heat the home because of ADS-related efficiency losses is calculated.

The system efficiency estimated for new HUD-code homes is about 60 percent (the actual calculated sample average is 56 percent). In the case of the MAP homes, the average system efficiency is closer to 80 percent. Given the physical limitations on the amount of insulation that can be installed in homes' floor systems and wrapped around the trunk ducts, and a best case approach to sealing the ducts in the plant and in the field, the 80 percent figure represents a practical limit on average system efficiency given the kinds of strategies contained in the MAP program. Some of the MAP homes have system efficiencies approaching 90 percent, but 80 percent is a more realistic average value.

Tables 3-14 through 3-16 show the annual heating energy requirements and associated energy costs for homes in North Carolina and New York built to current HUD thermal standards. North Carolina is in HUD thermal zone 2 (maximum allowable U_o-value of 0.096). However, since about one-half of the North Carolina homes have an envelope U_o-value that meets the HUD thermal zone 3 requirements, this level of thermal integrity is included in the analysis. The New York homes are all in HUD thermal zone 3 and correspondingly are depicted with an envelope U_o-value of 0.079.

Table 3-14 **Energy cost comparison in Raleigh, NC, Version 1 (U_o-value = 0.096)**

Condition	**Annual heating energy (kWh)**	**Annual heating cost ($)**	**Cost versus no duct case ($)**
No ducts	*8271*	*620*	*--*
Duct efficiency = 80%	*10339*	*775*	*155*
Duct efficiency = 60%	*13785*	*1034*	*414*

* Assumptions: 1400 ft^2 house with 10 percent glazing area, a natural air infiltration rate of 0.35 ACH (excluding additional ADS-induced infiltration), 65 °F interior temperature setpoint, electric resistance furnace, no thermostat setback, electricity cost of $0.075/kWh, and Raleigh, NC weather data.

Table 3-15 **Energy cost comparison in Raleigh, NC, Version 2 (U_o-value = 0.079)***

Condition	**Annual heating energy (kWh)**	**Annual heating cost ($)**	**Cost versus no duct case ($)**
No ducts	*6804*	*510*	*--*
Duct efficiency = 80%	*8505*	*638*	*128*
Duct efficiency = 60%	*11340*	*851*	*341*

* Assumptions: 1400 ft^2 house with 10 percent glazing area, a natural air infiltration rate of 0.35 ACH (excluding additional ADS-induced infiltration), 65 °F interior temperature setpoint, electric resistance furnace, no thermostat setback, electricity cost of $0.075/kWh, and Raleigh, NC weather data.

Table 3-16 **Energy cost comparison in Syracuse, NY (U_o-value of 0.079)***

Condition	**Annual heating energy (kWh)**	**Annual heating cost ($)**	**Cost versus no duct case ($)**
No ducts	*693*	*402*	*--*
Duct efficiency = 80%	*866*	*502*	*100*
Duct efficiency = 60%	*1155*	*670*	*268*

* Assumptions: 1400 ft^2 house with 10 percent glazing area, a natural air infiltration rate of 0.35 ACH (excluding additional ADS-induced infiltration), 65 °F interior temperature setpoint, no thermostat setback, Syracuse, NY weather data, natural gas furnace AFUE of 0.75, and gas cost of $0.58/therm

The cases examined include a home without ducts, although this is extremely rare in manufactured home construction. The difference in energy cost for the typical home in North Carolina built to HUD Zone 2 standards without ducts and a typical HUD-code home with ducts (i.e., 60 percent duct system efficiency) is about $414 per year. Assuming the same units built to Zone 3 thermal standards (U_o-value = 0.096) the difference is about $341. These operating cost differences are significant to most homeowners.

The homes in North Carolina have heat pumps and the impact of duct losses on performance of this equipment type is not well-established. From equation 2, as ΔT_e is reduced, the temperature-dependent part of the equation increases and the overall efficiency drops. Indeed, it is quite possible that if the heat pump register delivery temperature approaches room temperature, the heat delivery efficiency would near zero. In this study, ΔT_e was not measured for the heat pump homes as the tests were run in backup (electric resistance) mode. Although the heat pump operates with a design coefficient of performance (COP) of about 2, duct losses could reduce overall system efficiency to such a degree that the theoretical advantage of providing heat through a compression cycle is lost in practice.

In a harsher climate such as Syracuse, NY, with about 6,800 heating degree-days (versus about 3,500 in Raleigh, NC), there is also a significant cost difference between the unducted case and the home with a 60 percent duct system efficiency despite the use of less expensive natural gas. Electricity costs average about $22/million Btu in North Carolina compared with natural gas costs in upstate New York of about $5.80/million Btu. The additional annual heating cost is $268.

The next step is to assess the benefits associated with using the MAP program duct specifications listed in Table 3-17. The MAP requirements do not dramatically impact exterior duct leakage, but rather are intended to reduce conductive losses. Two levels of underfloor insulation upgrade are shown in the table, with R-22 the most common level in HUD-code homes. The other items are intended to reduce air leakage, such as improved mechanical fasteners, butyl tape or mastic for the end-caps of the trunk ducts, and a foam gasket for the furnace to duct system connector. The cost estimates also include added labor and in-plant inspection costs.

The costs for these improvements are based on research supporting MAP program (Baylon and Davis 1993). Both costs to the manufacturer and retail costs (to the consumer) are shown. The retail cost represents a mark-up of about 200 percent over the OEM cost, a standard industry mark-up.

A simple payback calculation is shown in Table 3-18 for the improvement from HUD-code levels of 60 percent duct system efficiency to the 80 percent efficient MAP levels. The North Carolina homes have either electric furnaces or heat pumps, the latter with an assumed overall seasonal COP of 2.0. For the homes in New York, the analysis is for a natural gas-fired furnace with an AFUE of 0.75. In all cases, the simple payback to the consumer from these improvements is less than three years.

Table 3-17 **Upgrades and costs**

Measure	**OEM cost ($)**	**Retail cost ($)**
R-22 to R-33 underfloor insulation	*100*	*210*
R-5 duct wrap	*14*	*29*
End cap tape/mastic	*5*	*11*
Furnace gasket	*1*	*2*
Added labor/inspection time	*10*	*10*
Total cost	*130*	*262*

Table 3-18 **Consumer economics for system upgrade**

Case	**Cost savings for 60 to 80% efficiency improvement ($/year)**	**Simple payback (years)**
NC (Uo-value = 0.079)	*213*	*1.2*
NC (Uo-value = 0.079 with heat pump)	*107*	*2.5*
NC (Uo-value = 0.096)	*259*	*1.0*
NC (Uo-value = 0.096 with heat pump)	*129*	*2.0*
NY (Uo-value = 0.079)	*168*	*1.6*

The improvements considered here would increase the manufacturing cost. Currently, the entire air distribution system costs in the vicinity of $100 to $200 and the items suggested would double this figure. Despite the compelling economic case, these kinds of improvements engendering a measurable increase in first cost are not likely to be adopted without a market push or regulatory intervention.

3.7. References

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4. Performance of air distribution systems in the cooling mode

4.1. Overview

The ADS cooling evaluation consisted of testing and assessing the performance of twelve manufactured homes; five located in Florida, five in Alabama, and two in North Carolina. Tests were conducted during the summer months of 1995. To characterize ADS performance, an array of tests was performed, including blower door, Duct Blaster™, tracer gas infiltration, and temperature and relative humidity monitoring. Data from these tests were used in computer simulations to determine seasonal cooling system performance.

The sample actually consists of two generic ADS design types. In Florida, all the homes have the cooling feed to the living spaces from above through attic-mounted flexible ducting. In the Alabama and North Carolina homes, the duct-work runs under the floor in the belly area and feeds up to the living spaces. The analysis attempts to depict the quantity of cooling energy delivered to the space without consideration of the efficacy of duct placement. That is, the study does not attempt to quantify the benefits associated with providing cool air from above rather than at floor level, although this factor certainly will impact comfort and probably total energy use.

The twelve homes tested in the field were analyzed using proprietary simulation software developed by the Florida Solar Energy Center titled *FSEC 3.0*. *FSEC 3.0* is a general building simulation program and provides detailed simulation of whole building systems, including energy, moisture, multi-zone air flows, and air distribution systems. Using the field data as program input, energy losses or penalties associated with residential distribution systems in manufactured homes were quantified for the three southeastern cooling climates.

The field test results clearly depicted the difficulties in attempting to characterize all manufactured homes using average or median results. For example, duct pressurization testing in Florida showed CFM_{25} readings ranging from 59 to 573 (or 4.4 percent to 50.8 percent of floor area), with an average of 199 (16.7 percent of floor area). Dropping the home with the leakiest ducts, Florida home 5 (FL-5), gives an average of 89 CFM_{25} (8.15 percent of floor area). In Alabama, the readings vary from 146 to 210 (or 10 percent to 17.8 percent of floor area), with an average of 189 CFM_{25} (13.7 percent of floor area). Repair of the ducts in Alabama House 5 (AL-5) dropped the CFM_{25} figure in this house from 189 to 88, suggesting that the performance of homes with identifiable leakage problems are good candidates for remedial repair. The leakage as a percentage of floor area dropped from 11.7 percent to 5.5 percent after the repair.

Air leakage through the exterior building envelope, an important variable in estimating ADS performance, varied widely among the sample homes. For example, data collected in the Florida homes using a blower door expressed in cubic feet per minute at 50 pascals of pressure (CFM_{50}) ranged from 1040 to 2060, with an average of 1380. Air change per hour rates at 50 pascals of pressure (ACH_{50}) ranged from 6.6 to 13.7, with an average of 8.6. Excluding Florida House 5 (FL-5), a notable outlier, these averages drop to 1210 CFM_{50} and 7.4 ACH_{50}, respectively. In Alabama, the blower door data yielded the following figures: CFM_{50} from 1143 to 3345, with an average of 2132. ACH_{50} ranged from 7.7 to 15.6, with an average of 11. Dropping the two single-section homes from this group yields averages of 2759 CFM_{50} and 13 ACH_{50}.

Two measures are used in the text to characterize the performance of the air distribution system. *Delivery* efficiency is an estimate of the percentage of cooling energy entering the distribution system compared to the amount exhausted into the living spaces. *System* efficiency is a better indicator of overall performance since it subsumes the *delivery* efficiency and accounts for the cooling energy that may be lost during transport through the ducts but eventually flows into the living space (referred to as regain) as well as other secondary energy effects (such as added whole house air infiltration) caused by the operation of the ADS. Because the system efficiency incorporates all losses as well as gains, it is a more realistic indicator of the performance of the duct system. System efficiencies for the ADS in the twelve sample homes are summarized in Tables 4-1 and 4-2 and illustrated graphically in Figures 1 and 2.

For the Florida homes, the delivery losses ranged between 12 and 30 percent. However, because the ducts are located in the attic, where the air temperature is typically higher, there is little or no net regain of the energy lost in the distribution systems. Rather, by driving hot attic air into the living spaces, the supply duct's leakage may impose an additional penalty on the home cooling energy use. The magnitude of this additional penalty increases with the amount of supply leak in the attic and the severity of the cooling climate. Therefore, for these homes, the system efficiencies are generally lower than the delivery efficiencies.

The analysis indicated that the delivery losses for the Alabama and North Carolina homes ranged between 20 and 30 percent. As noted, a portion of this loss is recovered by the conditioned spaces. This beneficial regain is primarily attributable to the duct system being located in the belly. The overall degradation in system efficiency for all homes due to the ADS, taking into account the regain, averaged about 18 percent with underfloor ducts losing about 11 percent on average and the overhead ducts in the Florida homes dropping to about 27 percent.

The latent component of the cooling load adds another layer of complication to the efficiency analysis. When the latent component is added into the overall cooling load, the ADS efficiency rises since there is virtually no diffusion of moisture across the duct walls. The only latent loss in the delivery system is through leakage. Further, the latent loss is more difficult to measure and therefore quantifying latent losses engenders more engineering assumptions and hypotheses.

The sensible portion, on the other hand, consists of conduction, leakage, and induced air infiltration components, features that can readily be measured by standard field tests. As a result, there is more confidence in the estimates of sensible efficiency, although adding in the latent component yields a better estimate of the overall impact of ADS on energy use. In most instances, efficiencies are expressed both ways: as a percentage of the sensible load and as total load (sensible plus latent).

As shown on Table 4-1, efficiency degradation as a percentage of total cooling load over the season averaged 29 percent for the Alabama and North Carolina homes, 32.9 percent for the Florida homes, and 30.6 percent for all homes. Taking into account secondary effects such as regain, total system efficiencies average 86.4 percent for the Alabama and North Carolina homes, 76.1 percent for the Florida homes and 82.1 percent for all homes. Results for the individual homes are shown on Table 4-2.

Table 4-1 **Cooling season system efficiency**

Loss source	**Overhead ducts** (FL homes - **%**)	**Underfloor ducts** (AL and NC homes - **%**)	**All homes** (%)
Sensible only			
Conduction	*9.8*	*10.8*	*10.4*
Leakage	*11.5*	*12.4*	*12.0*
Air infiltration	*5.0*	*4.5*	*4.7*
Sum of losses	***26.3***	***27.6***	***27.1***
Regain	***(0.7)***	***15.8***	***8.9***
System efficiency	***73.0***	***88.2***	***81.8***
Total sensible plus latent			
Conduction	*6.7*	*6.6*	*6.7*
Leakage	*11.8*	*12.9*	*12.4*
Air infiltration	*14.4*	*9.5*	*11.6*
Sum of losses	***32.9***	***29.0***	***30.6***
Regain	***(1.0)***	***15.4***	***12.7***
System efficiency	***76.1***	***86.4***	***82.1***

Table 4-2 **Estimate of system efficiencies**

House ID	**Cooling season** (%)		**Typical day** (%)		**Peak hour** (%)	
	Sensible	**Total**	**Sensible**	**Total**	**Sensible**	**Total**
AL-1	*87.0*	*85.0*	*84.1*	*82.6*	*78.1*	*77.3*
AL-2	*92.7*	*90.5*	*88.2*	*86.4*	*84.8*	*83.2*
AL-3	*86.4*	*85.3*	*80.5*	*79.7*	*73.3*	*73.2*
AL-4	*88.3*	*85.6*	*80.2*	*78.1*	*75.0*	*74.3*
AL-5	*85.4*	*83.9*	*79.7*	*78.3*	*78.2*	*76.2*
FL-1	*76.9*	*79.4*	*75.3*	*77.3*	*70.0*	*72.9*
FL-2	*80.6*	*82.9*	*79.7*	*81.3*	*74.2*	*76.0*
FL-3	*81.8*	*84.1*	*81.2*	*82.8*	*75.8*	*78.2*
FL-4	*63.4*	*67.7*	*63.8*	*67.4*	*55.3*	*60.0*
FL-5	*62.2*	*66.1*	*63.1*	*66.0*	*56.5*	*59.4*
NC-1	*87.5*	*86.8*	*82.8*	*81.8*	*78.6*	*82.4*
NC-2	*90.0*	*87.8*	*83.5*	*81.2*	*74.5*	*74.2*
Alabama						
Average	*87.9*	*86.0*	*82.5*	*81.0*	*77.9*	*76.8*
Median	*87.0*	*85.3*	*80.5*	*79.7*	*78.1*	*76.2*
Standard deviation	*2.6*	*2.3*	*3.2*	*3.1*	*3.9*	*3.5*
Florida						
Average	*73.0*	*76.1*	*72.6*	*75.0*	*66.4*	*69.4*
Median	*76.9*	*79.4*	*75.3*	*77.3*	*70.0*	*72.9*
Standard deviation	*8.5*	*7.6*	*7.7*	*7.0*	*8.8*	*7.9*
North Carolina						
Average	*88.8*	*87.3*	*83.1*	*81.5*	*76.6*	*78.3*
Median	*88.8*	*87.3*	*83.1*	*81.5*	*76.6*	*78.3*
Standard deviation	*1.2*	*0.5*	*0.3*	*0.3*	*2.0*	*4.1*
Combined averages						
Average	***81.8***	***82.1***	***78.5***	***78.6***	***72.9***	***74.0***
Median	***85.9***	***85.2***	***80.0***	***80.5***	***74.8***	***75.2***
Standard deviation	*9.4*	*7.3*	*7.4*	*5.8*	*8.3*	*7.0*

Figure 4-1 **Seasonal sensible system efficiencies**

Figure 4-2 **Seasonal total system efficiencies**

4.2. Field Tests

4.2.1. Description of homes - Florida

All Florida homes were double-section homes used as models in manufactured home developments. The homes were completely set up and ready for sale and occupancy. All had covered carports and attached utility rooms or screen porches which shaded most of one side of the home. No problems were evident in the workmanship used in the setup procedure. Four of the homes had package air conditioning (A/C) units and one a package heat pump. Equipment was site installed. Typically, two ducts would split from the supply side of the A/C unit and run to risers in each side of the manufactured home. These would then connect to the ceiling ductwork. The portion of the duct work that was underneath the home was raised above the ground by concrete blocks or panels of rigid insulating material. Typically, flexible duct was used in the attic space.

4.2.2. Description of homes - Alabama

All of the Alabama homes were less than five years old, and set up on homeowners' lots. Two were single-section homes. Both were well shaded with one of these having a covered porch along most of one side. The remaining three homes were double-sectioned and poorly shaded. Set up procedures ranged from adequate to sloppy. Cross over ducting was lying on the ground, and in some cases the juncture with the floor ducts had large gaps resulting in excessive leakage. Some homes had large holes in the belly wrap, often a result of post setup installation of wiring or cable.

Three of the homes used split A/C units, and two had interior heat pumps. All of the homes had metal underfloor ducts for delivering conditioned air to the living spaces.

4.2.3. Protocols

4.2.3.1. Blower Door

The objective of this test is to assess the tightness of the house envelope, determine the location of major leaks, and locate and quantify leaks in the air distribution system. House tightness is determined by blowing known quantities of air through the house envelope at specified house pressures. This testing was done with a Minneapolis Model 3 blower door equipped with an Energy Conservatory DG-1 digital micromanometer to determine building pressure differences across the envelope and to determine the pressure drop across the flow sensor in the fan unit. The blower door is capable of moving approximately 5000 CFM of air at a pressure difference of 50 Pascals. The flow of air through the fan can be determined (plus or minus 5 percent of actual flow) by measuring the pressure drop across the flow sensor.

Tests were conducted with all exterior doors and windows closed. The tests were then repeated with all the supply and return registers in the house sealed off by paper and tape. By subtraction, the airtightness of the duct system was also obtained. Airtightness of the house or duct system can be expressed in ACH_{50} (air changes per hour of the house volume at 50 Pa depressurization), CFM_{50} (air flow in cubic feet per minute into the house or duct system from outside the house at 50 Pa depressurization), or ELA_{50} (equivalent leak area of the house or duct system at 50 Pa depressurization).

Blower door testing was carried out in accordance with the ASTM E 779-87 "Test Method for Determining Air Leakage by Fan Pressurization" with minor modifications.

4.2.3.2. Pressure Pan

Pressure pan measurements are conducted with the blower door running in the depressurization mode (with house depressurized to -50 Pa). The pan is placed over each register individually, with all the others open. If there are no leaks close to the register being measured, only a small pressure difference will exist (<1 Pa). If leaks exist, the air being pulled into the house will cause a pressure difference to show up on the pressure pan. Readings as high as 30 Pa can occur for large leaks.

4.2.3.3. Duct System Airtightness

The duct system airtightness testing was done with a Minneapolis Duct Blaster™ equipped with an Energy Conservatory DG-2 digital micromanometer to determine the pressure differences across the duct system and to determine the pressure drop across the flow sensor in the fan unit. The Duct Blaster™ is capable of moving approximately 1400 CFM of air at a pressure difference of 25 pascals. The flow through the fan can be determined (plus or minus 3 percent of actual flow) by measuring the pressure drop across the flow sensor.

Duct system airtightness is tested by two procedures. In the first, the total leakage is found by attaching the Duct Blaster™ to the air handler after removing the blower. All registers are sealed. Using the supply plenum pressure tap or the closest, least leaky supply register as the reference point, measurements are taken at 10 and 25 Pa to determine the total leakage.

The second procedure measures the exterior leakage (that amount of duct leakage that leaves the house envelope). This two-point depressurization procedure is similar to the first, except now the building is also depressurized with the blower door. With the house at -25 Pa, the Duct Blaster™ is adjusted so the delta P between the house and the supply system is near 0. This Duct Blaster™ flow reading will give the exterior leakage.

The Duct Blaster™ can also be used to measure air flows by acting as a powered flowhood assembly. An air hood can be attached to the inlet of the Duct Blaster™ and then placed over the supply register to be measured. When the pressure drop across the hood with reference to the ambient is zero, the flow can be determined from the Duct Blaster™. The flow of the air handler fan can be determined under actual operating conditions by first measuring the static pressure of the supply duct. The Duct Blaster™ is attached to the air handler in such a way so that all of the air passing through the air handler fan must first pass through the Duct Blaster™. The Duct Blaster™ is adjusted until the original supply static pressure is duplicated. At this point, the flow of the air handler fan can be determined by knowing the flow through the Duct Blaster™.

4.2.3.4. Infiltration

Infiltration testing is used to determine the indoor-outdoor air exchange rate for the houses. The infiltration rates are established with the air handler on and off. This testing also helps to analyze the quality of HVAC installation and equipment. A tracer gas is used in measuring air exchange rates. The gas is injected into a building at some concentration. Air leakage dilutes the gas over time. The rate of decay in concentration is the air exchange rate.

The tracer gas used is sulfur hexaflouride (SF_6). It is a rare, nontoxic, and very stable gas which makes it suitable for testing purposes. Its concentration is measured by infrared, using in this case the Foxboro Miran 101 vapor analyzer. Two concentration measurements are taken. The first is from 0 to 50 parts per million (ppm), and the second from 0 to 5 ppm. An internal air pump moves air at 0.5 L/sec from a sample point to the internal chamber. A change in temperature can alter the zero drift of this device. This requires an initial warm-up period of about twenty minutes and zero calibrations throughout testing.

Two infiltration tests are performed. The first test measures natural infiltration. The air conditioner is turned on with the fan on continuously to stabilize air temperature. Then a preliminary check is made to assure that all supplies and returns are open, ventilation equipment off, and windows shut. The SF_6 is injected at the return until the concentration is stabilized, using small fans if necessary. All mechanical equipment is then turned off. In all infiltration tests measurements are made every ten minutes for an hour. The analyzer is zeroed every twenty minutes. Average drift is about 0.2 ppm. During testing, the indoor and outdoor ambient conditions are recorded.

The second test is conducted with the air conditioner on and the fan operating continuously. This test gives an idea of the air exchange rate and duct leakage under average summer conditions when homes are often closed. Tracer gas concentrations are monitored at three well-distributed locations, and at supply and return locations. The following formula is used to calculate return leak fraction (RLF):

$$RLF = (A-B) / (A-C) \quad \textbf{(5)}$$

where:

A = return concentration
B = supply concentration
C = buffer concentration

The air changes per hour are calculated by :

$$ACH = (60 / \text{number of minutes}) \ln (A/B) \quad \mathbf{(6)}$$

where:

A = average concentration at start
B = average concentration at end

4.2.3.5. Exterior Measurements

Exterior weather conditions at the time of testing are needed for the performance analysis. These include ambient temperature, relative humidity, and solar radiation. Temperature and relative humidity are measured with an Omega HX93 Humidity and Temperature Transmitter, and collected in a Campbell CR10 datalogger with weatherproof case that is set up adjacent to the home. Some of the remote measurements in the crawlspace and belly of the home are also collected with this datalogger.

Solar radiation in watts per meter squared is measured with a LI-COR LI-200SA Pyranometer Sensor, and also collected with the CR10 datalogger. This sensor is placed atop the tripod holding the datalogger. All of these measurements were taken at ten minute intervals.

4.2.3.6. Interior Measurements

Interior measurements and some belly measurements were taken with SmartReader dataloggers, palm-sized lithium battery powered monitors with a solid-state memory that can record 45 days of data collection at 2 minute intervals. This data is then averaged over a ten minute period to coincide with the CR10 data.

4.3. Analysis

4.3.1. Objectives

The overall goal of the analysis is to quantify the energy losses/penalty in residential distribution systems in manufactured homes for cooling climates of the Southeast. This is accomplished through the use of a simulation tool and data collected in the field from several manufactured homes.

4.3.2. Background

ASHRAE Standards SPC152P[8] provides a standard testing method for determining the steady-state and seasonal efficiencies of residential thermal distribution systems for heating climates. The efficiency of the air delivery system is defined as the ratio between the thermal energy leaving the terminal units of the distribution system (referenced to the room temperature) and the thermal energy entering the distribution system at the equipment heat exchanger. The energy loss in delivery is mainly from duct leakage and duct conduction losses. However, leakage in the air delivery system may cause increased infiltration in the building and lead to increased energy use, two factors not reflected in the delivery system efficiency.

The delivery efficiency can be estimated using the following equation provided by ASHRAE Standard SPC152P:

$$h = \frac{\sum j_i b_p \left(\mathrm{T}_{(reg(i))} - \mathrm{T}_{(room)}\right)}{j_{fan} b_p \left(\mathrm{T}_{(sup)} - \mathrm{T}_{(ret)}\right)} \quad \textbf{(7)}$$

where:

b_p = is the specific heat at constant reference (of air)
h = is the delivery efficiency
j_I = is the individual supply flow
j_{fan} = is the supply fan flow
$\mathrm{T}_{reg(i)}$ = is the individual supply temperature
T_{ret} = is the air temperature entering the return grilles
T_{room} = is the room air temperature
T_{sup} = is the return air temperature

Buildings are complex systems where the interaction of heat, moisture and air flow occur. Building sub-systems may include the thermal distribution system, equipment, envelope, fenestration, conditioned and unconditioned spaces. Airflows in a building are caused by pressure differences, both intended and unintended. As long as pressure differences and pathways exist between zones (including outdoors), caused by wind, stack or forced air flow, there will be an uncontrolled flow of air between the interior and exterior. Leakage can cause undesirable pressure gradients in the building and can lead to increased energy use due to added infiltration into conditioned zones from attic, garage or outdoors.

Figure 3 shows a schematic of possible flows in a building to further illustrate the complexity of the problem. An air distribution system feeds two conditioned zones. The supply ducts are assumed to be in the attic. A doorway separates the two zones and the return grille is located in Zone 2. The return air path for

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[8] Modera, M., 1994, "***A Standard Method of Test for Determining the Steady-State and Seasonal Efficiencies of Residential Thermal Distribution Systems***," ASHRAE STANDARD SPC-152P

Figure 4-3 **Schematic of building showing air pathways** the conditioned air from Zone 1 is through the doorway into the return grille. The various interactions as labeled in the figure are:

1. Air exchange between conditioned space and outdoors
2. Air exchange between Zone 1 and the attic
3. Air exchange between attic and outdoors
4. Air exchange between Zone 2 and the attic
5. Supply air duct leakage into the attic
6. Inter-zone airflow between conditional space
7. Return air duct leakage
8. Convection and radiation exchange at the external supply duct surfaces to the attic envelope
9. Convection and radiation at the supply duct external surface to the garage envelope
10. Supply air leak in the garage

It is evident that the mechanisms depicted above do not occur in isolation. Rather, the interactions are intrinsically connected to each other and must be examined in that light. For example, when the air handler is ON during the cooling season, energy lost in the supply ducts through leakage and conduction increases air conditioner loads. On the other hand, these losses tend to cool the attic, thus, reducing heat flow from the ceiling into the conditioned space. However, it is also possible that hot attic air might flow into the conditioned space, increasing the overall load on the building.

4.3.3. Simulation

The manufactured homes were analyzed using an in-house simulation software, *FSEC 3.0*. *FSEC 3.0* [9, 10] is a general building simulation program and provides detailed simulation of whole building systems, including energy, moisture, multi-zone air flows and air distribution systems simultaneously. Its capabilities include the following:

- zone thermal balance
- zone moisture balance
- zone contaminant balance, including radon
- heat and moisture transfer through the building envelope
- multi-zone airflow, including air distribution system
- zone and air distribution system pressures
- HVAC system models
- duct heat and moisture exchange.

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[9] Florida Solar Energy Center, 1992 **, *"FSEC 3.0: Florida Software for Enervironmental Computation*,**" Version 3.0, FSEC-GP-47-92

[10] Parker, D., P. Fairey, and L. Gu, 1993, " ***Simulation of the Effects of Duct Leakage and Heat Transfer on Residential Space Cooling Energy Use***," Energy and Buildings, V. 20, No. 2, pp. 97-113

Many of the capabilities of *FSEC 3.0* are derived from the software structure itself. *FSEC 3.0* consists primarily of three main sections. The first section is used to calculate temperature and moisture in the envelope. Users have a choice of either finite element method or conduction transfer function method. The second section is the building program that performs zone energy and moisture balances and calculates zonal temperatures and humidities. The third section is the HVAC and air flow program that calculates the air flows, pressures, temperatures and humidity ratios in the building and distribution system. All three sub-programs are fully coupled in an iterative loop and simulations are run until an overall convergence is attained.

4.3.4. Methodology

4.3.4.1. Basis

To perform the simulation modeling, a mathematical model of the house is built using the observed envelope, HVAC and distribution system characteristics. The program provides an hour-by-hour energy analysis for the entire cooling season using TMY weather data. Various components of the loads and losses are extracted. In contrast to the heating analysis, this approach relies less on monitored data, such as temperature and relative humidity, and more on the static characteristics of the house. Data such as temperatures and relative humidity are not direct inputs to the FSEC model; rather they serve only as guidance to ensure that the model does not deviate significantly from actual conditions.

4.3.4.2. Simulation Overview

The simulation consists of two major steps.

1. Using the airflow characteristics of the distribution system (layout, duct connectivity, duct sizes, duct leakage data) and envelope (zone volume, zone-to-zone leakage, and envelope leakage to outside) an airflow network model is constructed which gives the airflow pattern in the house when the system is ON. The driving force for this is the fan flow. This construct represents the node-to-node flows in the home when the system is ON, including flows in the duct system, leakage flows from ducts to buffer zones, flows from zone to zone and from zones to outside.
2. In the second step, a thermal model of the house is constructed from the layout and observed data such as dimension and thermal properties of the envelope, fenestration and duct system, an assumed internal gain profile in the building, cooling system capacity and flow.

Figure 4 shows a generic schematic of the airflow network for Alabama/North Carolina and Florida Homes, respectively, the major difference being the duct location.

Figure 4-4 **Schematic of air flows in typical manufactured homes**

4.3.4.3. Assumptions and Caveats

An initial set of runs for the Alabama homes was made assuming no leakage between the interstitial belly area and the ambient. That is, all the air leaking from the duct into the belly was being regained into the house. This was subsequently modified by assuming approximately a two square feet opening between the belly and ambient. The opening diverted more than half the duct leakage occurring in the belly to the ambient and the rest returned to the house.

Additionally, the initial sets of runs also indicated that in some homes with large leaks, the equipment was unable to maintain the desired set-point of 78 ^{o}F. Thus the same house maintained different indoor temperatures when the leaks and conduction losses were minimized and the resulting efficiencies calculated were skewed. This was later corrected by moderating the internal gain profile to ensure that the equipment maintained the desired cooling set-point of 78 ^{o}F with and without duct system losses in each of the homes.

In cooling climates, only the indoor temperature, not the humidity, is held constant, although ASHRAE suggests using 50 percent relative humidity as an appropriate indoor value. In fact, relative humidity will vary with time of day. The same house with and without duct losses will have different latent loads. This disparity between the humidities dislodges the reference for latent loads for the two cases. Comparisons between the latent loads must, therefore, be done with caution.

4.3.4.4. Simulation Procedure

The methodology used to analyze the homes is as follows:

- An *FSEC 3.0* input deck is prepared for each home, using data on the layout, envelope, fenestration and distribution system characteristics. The details of the protocols, actual data gathered, tests performed and the results of the tests are given in a later section. Test runs were made for a single day to ensure reasonableness of the results as compared to data collected in the field.
- Each home was simulated for the cooling season in the climate in which it is located. For example, for homes in the Orlando area, the cooling season was May through October. For Alabama homes, the cooling season June through October was used. For North Carolina, the cooling season was June through September.
- In addition, a typical summer day analysis was performed for each home in the climate where it was located.
- From each simulation load and loss data was extracted for the cooling season, typical summer day and peak hour of the typical summer day:

  Q_s: The sensible load on the house as removed by the cooling system. It includes all the energy removed to maintain the house at the desired set point including all the sensible loads and losses, sensible losses due to conduction and leakage in the duct system, and infiltration.

Q_l: The latent load on the house as seen by the cooling system. It includes all the energy removed to maintain the house at the balance point reached by the cooling system, latent losses due to conduction and leakage in the duct system, and all infiltration components.

P: Electric energy consumption by the cooling system

D_1: Sensible loss due to heat conduction from the supply duct to the buffer space. This includes losses from all ducts including cross-over ducts exposed to the appropriate buffer zone.

D_2: Latent loss due to moisture diffusion from the supply duct to the buffer space. This is usually very small and can be neglected.

D_3: Sensible loss due to heat conduction from the return duct to the buffer space.

D_4: Latent loss due to moisture diffusion from the return duct to the buffer space. This is usually very small and can be neglected.

D_5: Sensible loss due to leakage from the supply duct.

D_6: Latent loss due to leakage from the supply duct.

D_7: Sensible loss due to leakage from the return duct.

D_8: Latent loss due to leakage from the return duct.

I_s: Additional sensible load due to mechanically induced infiltration during system operation.

I_l: Additional latent load due to mechanically induced infiltration during system operation.

- Another set of simulations, known as the *optimum* configuration was simulated for each house representing the energy use and losses for the same home with the duct leakage and conduction kept to a minimum. A similar set of load and loss parameters, as above, are derived for the *optimum* configuration homes. Note that a third extension, either 'o' or 'a' will be added to the nomenclature above to represent optimum and actual configurations respectively.

4.3.5. Derived Results

Based on the loads and losses extracted from the simulation, several penalties and efficiencies are calculated for the *actual* and *optimum* configurations as described in the paragraphs that follow.

4.3.5.1. Derived Penalties

F_{sc}: Percent of sensible load lost due to conduction.

$$100 \times (D_1 + D_3)/Q_s$$

F_{sl}: Percent of sensible load lost due to sensible portion of leaks.

$$100 \times (D_5 + D_7)/Q_s$$

F_{si}: Additional sensible load due to forced infiltration due to system operation as a percent of sensible cooling provided by the system.

$$100 \times I_s/Q_s$$

F_{st}: The sum of all the above sensible losses as a percent of sensible cooling provided by the system.

$$100 \times (D_1 + D_3 + D_5 + D_7 + I_s)/Q_s$$

F_{lc}: Percent of latent load lost due to moisture diffusion.

$$100 \times (D_2 + D_4)/Q_l$$

F_{ll}: Percent of latent load lost due to latent portion of leak.

$$100 \times (D_6 + D_8)/Q_l$$

F_{li}: Additional latent load due to forced infiltration due to system operation as a percent of latent cooling provided by the system.

$$100 \times I_l/Q_l$$

F_{lt}: The sum of all the above latent losses as a percent of latent cooling provided by the system.

$$100 \times (D_2 + D_4 + D_6 + D_8 + I_l)/Q_l$$

F_{tc}: Percent of total load lost due to heat conduction and moisture diffusion.

$$100 \times (D_1 + D_2 + D_3 + D_4)/(Q_s + Q_l)$$

F_{tl}: Percent of total load lost due to duct leakage.

$$100 \times (D_5 + D_6 + D_7 + D_8)/(Q_s + Q_l)$$

F_{ti}: Additional sensible and latent load due to forced infiltration due to system operation as a percent of total cooling provided by the system.

$$100 \times (I_s + I_l)/(Q_s + Q_l)$$

F_{tt}: The sum of all the above total losses as a percent of total cooling provided by the system.

$$100 \times (D_1 + D_2 + D_3 + D_4 + D_5 + D_6 + D_7 + D_8 + I_s + I_l)/(Q_s + Q_l)$$

4.3.5.2. Derived efficiencies

Based on the loads and losses, sensible, latent, and total delivery and system efficiencies are calculated for the season, typical day, and peak hour of the typical day.

Delivery efficiency (**E_{del}**) - represents the portion of the cooling load removed by the cooling system that is directly delivered to the house. The portion that is not delivered is lost by conduction and leakage in the duct system. For the *actual* configuration, the efficiency expressions are as follows:

$$E_{dels} = 100 \times (1.0 - D_{sa} / Q_{sa}) \quad \textbf{(8)}$$

where:

E_{dels} = Sensible delivery efficiency
D_{sa} represents the total sensible loss in the duct system.

$$E_{dell} = 100 \times (1.0 - D_{la} / Q_{la}) \quad \textbf{(9)}$$

where:

E_{dell} = Latent delivery efficiency
D_{la} represents the total latent loss in the duct system.

$$E_{delt} =100 \times (1.0 - D_{ta} / Q_{ta}) \quad \textbf{(10)}$$

where:

E_{delt} = Total delivery efficiency
D_{ta} represents the total loss in the duct system.

As noted earlier, the delivery efficiency does not include regain or the penalty due to added infiltration.

System Efficiency (**E_{dis}**) - is the ratio of loads between the *optimum* and *actual* configurations. The system efficiency represents the cooling load of the *actual* configuration if its duct system conductive and leakage losses are minimized. The system efficiency is a comprehensive parameter that represents the net impact of minimizing duct losses on all aspects of the building load, including regain and forced infiltration. The system efficiency is found by applying the following formulae:

$$E_{diss} = 100 \times (Q_{so} / Q_{sa}) \quad \textbf{(11)}$$
$$E_{disl} = 100 \times (Q_{lo} / Q_{la}) \quad \textbf{(12)}$$
$$E_{dist} = 100 \times (Q_{to} / Q_{ta}) \quad \textbf{(13)}$$

where:

E_{diss} = Sensible system efficiency
E_{disl} = Latent system efficiency
E_{dist} = Total system efficiency

Note that the *optimum* configuration, although not representing a 100 percent efficient distribution system, does represent a highly efficient distribution system. ASHRAE Standards SPC152P does not fully address efficiency calculations for cooling climates, especially latent loads and losses. Thus, values of latent system efficiency, derived here, should only be considered qualitatively and used only to compare relative performance of the homes and not as absolute performance parameter indicators.

Regain (R_s) is part of the system efficiency and is defined as the portion of the duct losses that is recovered back into the house. Since the indoor humidity is not constant, only the sensible regain is calculated. This parameter is estimated as follows:

$$R_s = (Q_{so} - (Q_{sa} - D_{sa} - (I_{sa} - I_{so}))) / D_{sa} \quad \textbf{(14)}$$

4.4. Alabama results

The tables in this section present the results of the analysis for the five Alabama homes. Included are loads, losses, loss coefficients and efficiencies. In all Alabama homes the ducts are located in the underfloor belly area and the return is confined to the HVAC closet. TMY weather data for Tallahassee was used to simulate the cooling season for these homes.

4.4.1. Loads, Losses, penalties for five Alabama Homes

Table 4-3 **Component loads and losses for Alabama home 1 (AL-1)**

Load/loss component	**Cooling season** (kWh)		**Typical day** (kWh)		**Peak hour** (Wh)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible load	*3,929.26*	*4,516.96*	*47.31*	*56.25*	*4,100*	*5,250*
Latent load	*2,153.95*	*2,636.75*	*23.39*	*29.36*	*1,500*	*1,990*
Total power	*2,112.64*	*2,471.89*	*27.77*	*33.74*	*2,450*	*3,090*
Conduction losses						
Supply duct sensible	*17.77*	*350.63*	*0.23*	*4.32*	*20*	*400*
Supply duct latent	*2.28*	*1.38*	*0.02*	*0.01*	*0*	*0*
Return closet sensible	*0.55*	*14.53*	*0.00*	*0.14*	*0*	*10*
Return closet latent	*0.39*	*0.20*	*0.00*	*0.00*	*0*	*0*
Leakage losses						
Supply duct sensible	*3.03*	*466.98*	*0.04*	*5.81*	*20*	*550*
Supply duct latent	*1.67*	*286.57*	*0.02*	*3.19*	*10*	*225*
Return closet sensible	*6.69*	*11.34*	*0.15*	*0.25*	*50*	*60*
Return closet latent	*17.20*	*25.57*	*0.24*	*0.38*	*5*	*60*
Infiltration load						
Sensible infiltration load	*39.80*	*158.27*	*1.17*	*4.73*	*150*	*650*
Latent infiltration load	*133.85*	*468.56*	*1.96*	*7.28*	*150*	*650*
Summary results						
Total load	*6,083.21*	*7,153.71*	*70.70*	*85.61*	*5,600*	*7,240*
Total sensible duct loss	*28.04*	*843.48*	*0.41*	*10.52*	*90*	*1,020*
Total latent duct loss	*21.54*	*313.72*	*0.28*	*3.58*	*15*	*285*
Total duct loss	***49.58***	***1,157.20***	***0.69***	***14.10***	***105***	***1,305***

Total infiltration load	***173.65***	***626.83***	***3.13***	***12.01***	***300***	***1,300***

Table 4-4 **Component loss estimates for Alabama home 1 (AL-1)**

Component	**Cooling season** (%)		**Typical day** (%)		**Peak hour** (%)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible						
Conduction	*0*	*8*	*0*	*8*	*0*	*8*
Leakage	*0*	*11*	*0*	*11*	*2*	*12*
Added infiltration	*1*	*4*	*2*	*8*	*4*	*12*
Total sensible loss	***2***	***22***	***3***	***27***	***6***	***32***
Latent						
Conduction	*0*	*0*	*0*	*0*	*0*	*0*
Leakage	*1*	*12*	*1*	*12*	*1*	*14*
Added infiltration	*6*	*18*	*8*	*25*	*10*	*33*
Total latent loss	***7***	***30***	***10***	***37***	***11***	***47***
Sensible plus latent loss						
Conduction	*0*	*5*	*0*	*5*	*0*	*6*
Leakage	*0*	*11*	*1*	*11*	*2*	*12*
Added infiltration	*3*	*9*	*4*	*14*	*5*	*18*
Total sensible plus latent loss	***4***	***25***	***5***	***30***	***7***	***36***

Table 4-5 **Delivery and system efficiencies for Alabama home 1 (AL-1)**

Component	**Cooling season** (%)	**Typical day** (%)	**Peak hour** (%)
Delivery efficiency			
Sensible	*81*	*81*	*81*
Latent	*88*	*88*	*86*
Total delivery efficiency	***84***	***84***	***82***
System efficiency			
Sensible	*87*	*84*	*78*
Latent	*82*	*80*	*75*
Total system efficiency	***85***	***83***	***77***
Estimated regain (sensible only)	***44***	***49***	***36***

Table 4-6 **Component loads and losses for Alabama home 2 (AL-2)**

Load/loss component	**Cooling season** (kWh)		**Typical day** (kWh)		**Peak hour** (Wh)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible load	5,242.39	5,657.26	63.78	72.28	5,600	6,600
Latent load	3,144.34	3,612.98	35.49	42.61	2,350	2,950
Total power	2,894.41	3,191.70	38.92	45.11	3,400	4,000
Conduction losses						
Supply duct sensible	45.29	589.87	0.55	7.31	50	700
Supply duct latent	5.49	2.01	0.05	0.01	0	0
Return closet sensible	0.88	27.37	0.01	0.27	0	25
Return closet latent	0.38	0.13	0.00	0.00	0	0
Leakage losses						
Supply duct sensible	8.95	953.50	0.10	11.05	5	1,000
Supply duct latent	6.17	689.24	0.05	6.56	5	450
Return closet sensible	7.44	38.64	0.16	0.87	25	109
Return closet latent	16.69	77.44	0.24	1.20	5	109
Infiltration load						
Sensible infiltration load	48.08	238.82	1.42	7.27	175	950
Latent infiltration load	141.12	624.21	2.12	10.05	175	850
Summary results						
Total load	8,386.73	9,270.24	99.27	114.89	7,950	9,550
Total sensible duct loss	62.56	1,609.38	0.82	19.50	80	1,834
Total latent duct loss	28.73	768.82	0.35	7.76	10	559
Total duct loss	**91.29**	**2,378.20**	**1.17**	**27.26**	**90**	**2,393**
Total infiltration load	**189.20**	**863.03**	**3.54**	**17.32**	**350**	**1,800**

Table 4-7 **Component loss estimates for Alabama home 2 (AL-2)**

Component	**Cooling season** (%)		**Typical day** (%)		**Peak hour** (%)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible						
Conduction	1	11	1	10	1	11
Leakage	0	18	0	16	1	17
Added infiltration	1	4	2	10	3	14
Total sensible loss	**2**	**33**	**4**	**37**	**5**	**42**
Latent						
Conduction	0	0	0	0	0	0
Leakage	1	21	1	18	0	19
Added infiltration	4	17	6	24	7	29
Total latent loss	**5**	**39**	**7**	**42**	**8**	**48**
Sensible plus latent loss						
Conduction	1	7	1	7	1	8
Leakage	0	19	1	17	1	17

Added infiltration	2	9	4	15	4	19
Total sensible plus latent loss	**3**	**35**	**5**	**39**	**6**	**44**

Table 4-8 **Delivery and system efficiencies for Alabama home 2 (AL-2)**

Component	**Cooling season** (%)	**Typical day** (%)	**Peak hour** (%)
Delivery efficiency			
Sensible	72	73	72
Latent	79	82	81
Total delivery efficiency	**74**	**76**	**75**
System efficiency			
Sensible	93	88	85
Latent	87	83	80
Total system efficiency	**90**	**86**	**83**
Estimated regain (sensible only)	**86**	**86**	**88**

Table 4-9 **Component loads and losses for Alabama home 3 (AL-3)**

Load/loss component	**Cooling season** (kWh)		**Typical day** (kWh)		**Peak hour** (Wh)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible load	3,460.57	4,007.15	41.16	51.16	3,300	4,500
Latent load	2,157.54	2,581.57	24.03	30.68	1,500	2,060
Total power	1,809.47	2,115.99	23.79	30.01	1,900	2,500
Conduction losses						
Supply duct sensible	19.10	395.30	0.24	5.23	15	460
Supply duct latent	2.05	1.26	0.02	0.01	0	0
Return closet sensible	0.47	12.49	0.00	0.08	0	0
Return closet latent	0.33	0.17	0.00	0.00	0	0
Leakage losses						
Supply duct sensible	2.65	371.72	0.03	4.89	5	435
Supply duct latent	1.66	255.91	0.02	3.14	5	210
Return closet sensible	7.23	12.78	0.16	0.30	10	40
Return closet latent	16.46	25.91	0.23	0.40	10	40
Infiltration load						
Sensible infiltration load	53.46	175.50	1.50	5.25	160	650
Latent infiltration load	149.13	431.74	2.17	7.02	160	600
Summary results						
Total load	5,618.11	6,588.72	65.19	81.84	4,800	6,560
Total sensible duct loss	29.45	792.29	0.43	10.50	30	935
Total latent duct loss	20.50	283.25	0.27	3.55	15	250
Total duct loss	**49.95**	**1,075.54**	**0.70**	**14.06**	**45**	**1,185**
Total infiltration load	**202.59**	**607.24**	**3.67**	**12.27**	**320**	**1,250**

Table 4-10 **Component loss estimates for Alabama home 3** (**AL-3)**

Component	**Cooling season** (%)		**Typical day** (%)		**Peak hour** (%)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible						
Conduction	*1*	*10*	*1*	*10*	*0*	*10*
Leakage	*0*	*10*	*0*	*10*	*0*	*11*
Added infiltration	*2*	*4*	*4*	*10*	*5*	*14*
Total sensible loss	***2***	***24***	***5***	***31***	***6***	***35***
Latent						
Conduction	*0*	*0*	*0*	*0*	*0*	*0*
Leakage	*1*	*11*	*1*	*12*	*1*	*12*
Added infiltration	*7*	*17*	*9*	*23*	*11*	*29*
Total latent loss	***8***	***28***	***10***	***34***	***12***	***41***
Sensible plus latent loss						
Conduction	*0*	*6*	*0*	*7*	*0*	*7*
Leakage	*0*	*10*	*1*	*11*	*1*	*11*
Added infiltration	*4*	*9*	*6*	*15*	*7*	*19*
Total sensible plus latent loss	***4***	***26***	***7***	***32***	***8***	***37***

Table 4-11 **Delivery and system efficiencies for Alabama home 3** (**AL-3)**

Component	**Cooling season** (%)	**Typical day** (%)	**Peak hour** (%)
Delivery efficiency			
Sensible	*80*	*79*	*79*
Latent	*89*	*88*	*88*
Total delivery efficiency	***84***	***83***	***82***
System efficiency			
Sensible	*86*	*80*	*73*
Latent	*84*	*78*	*73*
Total system efficiency	***85***	***80***	***73***
Estimated regain (**sensible only)**	***46***	***40***	***24***

Table 4-12 **Component loads and losses for Alabama home 4 (AL-4)**

Load/loss component	**Cooling season** (kWh)		**Typical day** (kWh)		**Peak hour** (Wh)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible load	5,294.31	5,995.11	57.07	71.18	4,500	6,000
Latent load	3,119.99	3,839.02	31.05	41.71	2,000	2,750
Total power	2,936.84	3,423.33	34.22	44.05	2,750	3,750
Conduction losses						
Supply duct sensible	37.97	646.50	0.43	8.07	25	725
Supply duct latent	4.24	2.21	0.04	0.01	0	0
Return closet sensible	0.40	29.70	0.00	0.26	0	10
Return closet latent	0.40	0.16	0.00	0.00	0	0
Leakage losses						
Supply duct sensible	5.33	786.14	0.05	9.35	0	800
Supply duct latent	3.15	507.90	0.03	5.53	0	355
Return closet sensible	1.22	5.31	0.03	0.12	0	10
Return closet latent	3.31	12.28	0.04	0.17	0	10
Infiltration load						
Sensible infiltration load	60.06	261.72	1.64	7.59	210	990
Latent infiltration load	210.89	766.22	2.72	11.14	205	890
Summary results						
Total load	8,414.30	9,834.13	88.12	112.89	6,500	8,750
Total sensible duct loss	44.92	1,467.65	0.51	17.79	25	1,545
Total latent duct loss	11.10	522.55	0.11	5.71	0	365
Total duct loss	**56.02**	**1,990.20**	**0.62**	**23.50**	**25**	**1,910**
Total infiltration load	**270.95**	**1,027.94**	**4.36**	**18.73**	**415**	**1,880**

Table 4-13 **Component loss estimates for Alabama home 4 (AL-4)**

Component	**Cooling season** (%)		**Typical day** (%)		**Peak hour** (%)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible						
Conduction	1	11	1	12	1	12
Leakage	0	13	0	13	0	14
Added infiltration	1	4	3	11	5	17
Total sensible loss	**2**	**29**	**4**	**36**	**5**	**42**
Latent						
Conduction	0	0	0	0	0	0
Leakage	0	14	0	14	0	13
Added infiltration	7	20	9	27	10	32
Total latent loss	**7**	**34**	**9**	**40**	**10**	**46**
Sensible plus latent loss						
Conduction	1	7	1	7	0	8
Leakage	0	13	0	13	0	13

Added infiltration	*3*	*10*	*5*	*17*	*6*	*21*
Total sensible plus latent loss	***4***	***31***	***6***	***37***	***7***	***43***

Table 4-14 **Delivery and system efficiencies for Alabama home 4 (AL-4)**

Component	**Cooling season** (%)	**Typical day** (%)	**Peak hour** (%)
Delivery efficiency			
Sensible	*76*	*75*	*74*
Latent	*86*	*86*	*87*
Total delivery efficiency	***80***	***79***	***78***
System efficiency			
Sensible	*88*	*80*	*75*
Latent	*81*	*74*	*73*
Total system efficiency	***86***	***78***	***74***
Estimated regain (sensible only)	***66***	***54***	***53***

Table 4-15 **Component loads and losses for Alabama home 5 (AL-5)**

Load/loss component	**Cooling season** (kWh)		**Typical day** (kWh)		**Peak hour** (Wh)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible load	*4,928.01*	*5,773.24*	*60.79*	*76.23*	*5,125*	*6,550*
Latent load	*3,187.62*	*3,902.08*	*36.43*	*47.89*	*2,300*	*3,200*
Total power	*2,797.28*	*3,322.54*	*37.84*	*48.46*	*3,050*	*4,200*
Conduction losses						
Supply duct sensible	*46.14*	*774.49*	*0.59*	*10.45*	*50*	*915*
Supply duct latent	*5.31*	*2.52*	*0.05*	*0.02*	*0*	*0*
Return closet sensible	*0.25*	*24.12*	*0.00*	*0.28*	*0*	*25*
Return closet latent	*0.32*	*0.11*	*0.00*	*0.00*	*0*	*0*
Leakage losses						
Supply duct sensible	*5.59*	*747.69*	*0.07*	*9.88*	*0*	*855*
Supply duct latent	*3.62*	*509.02*	*0.04*	*6.25*	*0*	*420*
Return closet sensible	*0.66*	*3.67*	*0.01*	*0.08*	*0*	*5*
Return closet latent	*1.45*	*6.95*	*0.02*	*0.11*	*0*	*0*
Infiltration load						
Sensible infiltration load	*67.05*	*321.92*	*1.98*	*9.81*	*225*	*1,100*
Latent infiltration load	*189.96*	*794.52*	*2.88*	*13.03*	*225*	*1,100*
Summary results						
Total load	*8,115.63*	*9,675.32*	*97.22*	*124.12*	*7,425*	*9,750*
Total sensible duct loss	*52.64*	*1,549.97*	*0.67*	*20.69*	*50*	*1,800*
Total latent duct loss	*10.70*	*518.60*	*0.11*	*6.38*	*0*	*420*
Total duct loss	***63.34***	***2,068.57***	***0.79***	***27.07***	***50***	***2,220***
Total infiltration load	***257.01***	***1,116.44***	***4.86***	***22.84***	***450***	***2,200***

Table 4-16 **Component loss estimates for Alabama home 5** (**AL-5)**

Component	**Cooling season** (%)		**Typical day** (%)		**Peak hour** (%)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible						
Conduction	*1*	*14*	*1*	*14*	*1*	*14*
Leakage	*0*	*13*	*0*	*13*	*0*	*13*
Added infiltration	*1*	*6*	*3*	*13*	*4*	*17*
Total sensible loss	***2***	***32***	***4***	***40***	***5***	***44***
Latent						
Conduction	*0*	*0*	*0*	*0*	*0*	*0*
Leakage	*0*	*13*	*0*	*13*	*0*	*13*
Added infiltration	*6*	*20*	*8*	*27*	*10*	*34*
Total latent loss	***6***	***34***	***8***	***41***	***10***	***48***
Sensible plus latent loss						
Conduction	*1*	*8*	*1*	*9*	*1*	*10*
Leakage	*0*	*13*	*0*	*13*	*0*	*13*
Added infiltration	*3*	*12*	*5*	*18*	*6*	*23*
Total sensible plus latent loss	***4***	***33***	***6***	***40***	***7***	***45***

Table 4-17 **Delivery and system efficiencies for Alabama home 5** (**AL-5)**

Component	**Cooling season** (%)	**Typical day** (%)	**Peak hour** (%)
Delivery efficiency			
Sensible	*73*	*73*	*73*
Latent	*87*	*87*	*87*
Total delivery efficiency	***79***	***78***	***77***
System efficiency			
Sensible	*85*	*80*	*78*
Latent	*82*	*76*	*72*
Total system efficiency	***84***	***78***	***76***
Estimated regain (**sensible only)**	***62***	***63***	***69***

4.4.2. Summary of efficiencies -- Alabama Homes

A quick review of the efficiencies in the previous tables reveal that the latent delivery efficiencies are always considerably higher than the corresponding sensible delivery efficiencies. Since there is virtually no diffusion of moisture across the duct walls, the only latent loss in the delivery system is leakage, unlike the sensible portion which accounts for both conduction and leakage. The latent system efficiencies, on the other hand, are always lower than the corresponding sensible component because of different balance point relative humidities between the *optimum* and *actual* configurations. The total (i.e. sensible plus latent) delivery and system efficiencies lie somewhere between the sensible and latent components. In view of this, it is recommended that the sensible efficiencies be considered as the primary indicator of duct system performance followed by the total efficiencies. Accordingly, only the sensible and total efficiencies are summarized here.

Table 4-18 **Sensible efficiencies for Alabama homes**

House ID	**Sensible delivery efficiency** (%)			**Sensible system efficiency** (%)		
	Season	**Typical day**	**Peak hour**	**Season**	**Typical day**	**Peak hour**
AL-1	*81.30*	*81.30*	*80.60*	*87.00*	*84.10*	*78.10*
AL-2	*71.60*	*73.00*	*72.20*	*92.70*	*88.20*	*84.80*
AL-3	*80.20*	*79.50*	*79.20*	*86.40*	*80.50*	*73.30*
AL-4	*75.50*	*75.00*	*74.30*	*88.30*	*80.20*	*75.00*
AL-5	*73.20*	*72.90*	*72.50*	*85.40*	*79.70*	*78.20*

Table 4-19 **Total efficiencies for Alabama homes**

House ID	**Sensible delivery efficiency** (%)			**Sensible system efficiency** (%)		
	Season	**Typical day**	**Peak hour**	**Season**	**Typical day**	**Peak hour**
AL-1	*83.80*	*83.50*	*82.00*	*85.00*	*82.60*	*77.30*
AL-2	*74.30*	*76.30*	*74.90*	*90.50*	*86.40*	*83.20*
AL-3	*83.70*	*82.80*	*81.90*	*85.30*	*79.70*	*73.20*
AL-4	*79.80*	*79.20*	*78.20*	*85.60*	*78.10*	*74.30*
AL-5	*78.60*	*78.20*	*77.20*	*83.90*	*78.30*	*76.20*

For the Alabama homes, the sensible delivery efficiencies vary anywhere between 72 and 81 percent indicating a 20-30 percent potential sensible energy loss associated with the delivery system. The total delivery efficiencies, however, vary between 73 percent and 82 percent. Because regain (sometimes called recovery) is higher than infiltration load, the system efficiencies are generally higher than the delivery efficiencies. The *optimum* system efficiency simply represents the fraction of the original *actual* load which can be attained by a nearly perfect distribution system. Sensible system efficiencies range between 72 and 89 percent indicating that 11 to 28 percent reductions in cooling energy use are possible by attempting to perfect the distribution system.

4.5. Florida results

The tables in this section present the results of the analysis for the five Florida homes. The results presented include loads, losses, loss coefficients and efficiencies. In all Florida homes the supply ducts are located in the attic and also run through an interior wall chase, and then through the crawl space to the outside packaged air conditioner. The Florida homes are also unique in that they have a return duct entering into the same chase and running parallel to the supply duct and terminating at the air conditioner. TMY weather data for Orlando was used to simulate the cooling season for these homes as this was the closest city for which hourly weather data was available.

4.5.1. Loads, Losses, penalties for five Florida Homes

Table 4-20 **Component loads and losses for Florida home 1 (FL-1)**

Load/loss component	**Cooling season** (kWh)		**Typical day** (kWh)		**Peak hour** (Wh)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible load	*7,643.80*	*9,944.50*	*62.59*	*83.17*	*4,552*	*6,500*
Latent load	*3,654.00*	*4,282.40*	*26.77*	*32.50*	*1,500*	*1,800*
Total power	*4,054.80*	*5,115.80*	*34.43*	*44.90*	*2,550*	*3,500*
Conduction losses						
Supply duct sensible	*101.71*	*967.66*	*0.82*	*7.88*	*80*	*775*
Supply duct latent	*7.27*	*5.11*	*0.05*	*0.03*	*0*	*0*
Return duct sensible	*7.35*	*58.82*	*0.05*	*0.42*	*0*	*70*
Return duct latent	*0.65*	*0.40*	*0.00*	*0.00*	*0*	*0*
Leakage losses						
Supply duct sensible	*12.93*	*990.73*	*0.11*	*8.25*	*0*	*625*
Supply duct latent	*6.20*	*430.56*	*0.05*	*3.25*	*0*	*180*
Return duct sensible	*4.37*	*14.77*	*0.06*	*0.20*	*0*	*20*
Return duct latent	*14.45*	*48.80*	*0.16*	*0.52*	*0*	*20*
Infiltration load						
Sensible infiltration load	*100.71*	*351.27*	*1.57*	*5.36*	*200*	*800*
Latent infiltration load	*380.13*	*1,286.73*	*4.10*	*13.89*	*200*	*650*
Summary results						
Total load	*11,297.8*	*14,226.9*	*89.36*	*115.67*	*6,052*	*8,300*
Total sensible duct loss	*126.36*	*2,031.98*	*1.03*	*16.75*	*80*	*1,490*
Total latent duct loss	*28.57*	*484.87*	*0.25*	*3.80*	*0*	*200*
Total duct loss	***154.93***	***2,516.85***	***1.28***	***20.55***	***80***	***1,690***
Total infiltration load	***480.84***	***1,638.00***	***5.67***	***19.25***	***400***	***1,450***

Table 4-21 **Component loss estimates for Florida home 1 (FL-1)**

Component	**Cooling season** (%)		**Typical day** (%)		**Peak hour** (%)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible						
Conduction	*1*	*10*	*1*	*10*	*2*	*13*
Leakage	*0*	*10*	*0*	*10*	*0*	*10*
Added infiltration	*1*	*4*	*3*	*6*	*4*	*12*
Total sensible loss	***3***	***24***	***4***	***27***	***6***	***35***
Latent						
Conduction	*0*	*0*	*0*	*0*	*0*	*0*
Leakage	*1*	*11*	*1*	*12*	*0*	*11*
Added infiltration	*10*	*30*	*15*	*43*	*13*	*36*
Total latent loss	***11***	***41***	***16***	***54***	***13***	***47***
Sensible plus latent loss						
Conduction	*1*	*7*	*1*	*7*	*1*	*10*
Leakage	*0*	*10*	*0*	*11*	*0*	*10*
Added infiltration	*4*	*12*	*6*	*17*	*7*	*17*
Total sensible plus latent loss	***6***	***29***	***8***	***34***	***8***	***38***

Table 4-22 **Delivery and system efficiencies for Florida home 1 (FL-1)**

Component	**Cooling season** (%)	**Typical day** (%)	**Peak hour** (%)
Delivery efficiency			
Sensible	*80*	*80*	*77*
Latent	*89*	*88*	*89*
Total delivery efficiency	***82***	***82***	***80***
System efficiency			
Sensible	*77*	*75*	*70*
Latent	*85*	*82*	*83*
Total system efficiency	***79***	***77***	***73***
Estimated regain (sensible only)	***-1***	***0***	***10***

Table 4-23 **Component loads and losses for Florida home 2 (FL-2)**

Load/loss component	**Cooling season** (kWh)		**Typical day** (kWh)		**Peak hour** (Wh)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible load	8,255.00	10,239.1	69.98	87.77	4,900	6,600
Latent load	4,248.20	4,839.70	32.29	38.02	1,750	2,150
Total power	4,473.60	5,439.30	39.24	48.55	2,750	3,600
Conduction losses						
Supply duct sensible	96.47	931.65	0.78	7.63	70	750
Supply duct latent	6.86	5.46	0.05	0.04	0	0
Return duct sensible	7.23	62.19	0.05	0.46	0	50
Return duct latent	0.61	0.45	0.00	0.00	0	0
Leakage losses						
Supply duct sensible	16.34	670.90	0.14	5.73	0	330
Supply duct latent	8.43	320.14	0.06	2.50	0	150
Return duct sensible	3.55	10.38	0.05	0.14	0	10
Return duct latent	11.18	32.80	0.13	0.37	0	10
Infiltration load						
Sensible infiltration load	114.29	330.21	1.81	5.12	200	640
Latent infiltration load	408.35	1,154.54	4.62	12.93	200	690
Summary results						
Total load	12,503.2	15,078.8	102.27	125.79	6,650	8,750
Total sensible duct loss	123.59	1,675.12	1.02	13.97	70	1,140
Total latent duct loss	27.08	358.85	0.24	2.91	0	160
Total duct loss	**150.67**	**2,033.97**	**1.26**	**16.87**	**70**	**1,300**
Total infiltration load	**522.64**	**1,484.75**	**6.43**	**18.05**	**400**	**1,330**

Table 4-24 **Component loss estimates for Florida home 2 (FL-2)**

Component	**Cooling season** (%)		**Typical day** (%)		**Peak hour** (%)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible						
Conduction	1	10	1	9	1	12
Leakage	0	7	0	7	0	5
Added infiltration	1	3	3	6	4	10
Total sensible loss	**3**	**20**	**4**	**22**	**6**	**27**
Latent						
Conduction	0	0	0	0	0	0
Leakage	0	7	1	8	0	7
Added infiltration	10	24	14	34	11	32
Total latent loss	**10**	**31**	**15**	**42**	**11**	**40**
Sensible plus latent loss						
Conduction	1	7	1	6	1	9
Leakage	0	7	0	7	0	6
Added infiltration	4	10	6	14	6	15

Total sensible plus latent loss	***5***	***23***	***8***	***28***	***7***	***30***

Table 4-25 **Delivery and system efficiencies for Florida home 2 (FL-2)**

Component	**Cooling season** (%)	**Typical day** (%)	**Peak hour** (%)
Delivery efficiency			
Sensible	*84*	*84*	*83*
Latent	*93*	*92*	*93*
Total delivery efficiency	***87***	***87***	***85***
System efficiency			
Sensible	*81*	*80*	*74*
Latent	*88*	*85*	*81*
Total system efficiency	***83***	***81***	***76***
Estimated regain (sensible only)	***-6***	***-4***	***-11***

Table 4-26 **Component loads and losses for Florida home 3 (FL-3)**

Load/loss component	**Cooling season** (kWh)		**Typical day** (kWh)		**Peak hour** (Wh)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible load	*8,324.10*	*10,178.4*	*70.57*	*86.88*	*5,000*	*6,600*
Latent load	*4,385.40*	*4,926.80*	*33.42*	*38.65*	*1,800*	*2,100*
Total power	*4,546.90*	*5,443.10*	*39.90*	*48.42*	*2,900*	*3,600*
Conduction losses						
Supply duct sensible	*102.99*	*1,000.94*	*0.85*	*8.31*	*90*	*800*
Supply duct latent	*6.97*	*5.88*	*0.05*	*0.04*	*0*	*0*
Return duct sensible	*7.07*	*60.44*	*0.05*	*0.44*	*0*	*60*
Return duct latent	*0.59*	*0.47*	*0.00*	*0.00*	*0*	*0*
Leakage losses						
Supply duct sensible	*11.04*	*626.97*	*0.09*	*5.34*	*0*	*425*
Supply duct latent	*5.83*	*306.28*	*0.04*	*2.39*	*0*	*150*
Return duct sensible	*3.47*	*8.84*	*0.05*	*0.12*	*0*	*10*
Return duct latent	*10.58*	*27.25*	*0.12*	*0.30*	*0*	*10*
Infiltration load						
Sensible infiltration load	*116.07*	*285.23*	*1.82*	*4.41*	*200*	*575*
Latent infiltration load	*398.09*	*972.53*	*4.51*	*10.86*	*200*	*575*
Summary results						
Total load	*12,709.5*	*15,105.2*	*103.99*	*125.53*	*6,800*	*8,700*
Total sensible duct loss	*124.57*	*1,697.19*	*1.04*	*14.21*	*90*	*1,295*
Total latent duct loss	*23.97*	*339.88*	*0.21*	*2.74*	*0*	*160*
Total duct loss	***148.54***	***2,037.07***	***1.25***	***16.95***	***90***	***1,455***
Total infiltration load	***514.16***	***1,257.76***	***6.33***	***15.27***	***400***	***1,150***

Table 4-27 **Component loss estimates for Florida home 3** (**FL-3)**

Component	**Cooling season** (%)		**Typical day** (%)		**Peak hour** (%)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible						
Conduction	*1*	*10*	*1*	*10*	*2*	*13*
Leakage	*0*	*6*	*0*	*6*	*0*	*7*
Added infiltration	*1*	*3*	*3*	*5*	*4*	*9*
Total sensible loss	***3***	***19***	***4***	***21***	***6***	***28***
Latent						
Conduction	*0*	*0*	*0*	*0*	*0*	*0*
Leakage	*0*	*7*	*0*	*7*	*0*	*8*
Added infiltration	*9*	*20*	*13*	*28*	*11*	*27*
Total latent loss	***10***	***27***	***14***	***35***	***11***	***35***
Sensible plus latent loss						
Conduction	*1*	*7*	*1*	*7*	*1*	*10*
Leakage	*0*	*6*	*0*	*6*	*0*	*7*
Added infiltration	*4*	*8*	*6*	*12*	*6*	*13*
Total sensible plus latent loss	***5***	***22***	***7***	***26***	***7***	***30***

Table 4-28 **Delivery and system efficiencies for Florida home 3** (**FL-3)**

Component	**Cooling season** (%)	**Typical day** (%)	**Peak hour** (%)
Delivery efficiency			
Sensible	*83*	*84*	*80*
Latent	*93*	*93*	*92*
Total delivery efficiency	***87***	***86***	***83***
System efficiency			
Sensible	*82*	*81*	*76*
Latent	*89*	*86*	*86*
Total system efficiency	***84***	***83***	***78***
Estimated regain (**sensible only)**	***1***	***3***	***5***

Table 4-29 **Component loads and losses for Florida home 4 (FL-4)**

Load/loss component	**Cooling season** (kWh)		**Typical day** (kWh)		**Peak hour** (Wh)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible load	6,820.60	10,756.2	63.39	99.28	4,700	8,500
Latent load	4,106.90	5,382.00	34.38	45.71	2,000	2,600
Total power	4,067.70	6,099.10	38.94	58.55	3,000	4,750
Conduction losses						
Supply duct sensible	120.49	1,142.28	0.99	9.50	100	950
Supply duct latent	7.78	4.77	0.07	0.03	0	0
Return duct sensible	7.14	54.63	0.05	0.41	0	50
Return duct latent	0.51	0.26	0.00	0.00	0	0
Leakage losses						
Supply duct sensible	12.89	1,703.10	0.12	15.73	0	1,300
Supply duct latent	7.78	857.83	0.07	7.28	0	430
Return duct sensible	4.08	25.14	0.06	0.36	0	40
Return duct latent	10.58	68.25	0.13	0.83	0	50
Infiltration load						
Sensible infiltration load	94.96	720.61	1.51	11.09	180	1,300
Latent infiltration load	269.03	2,100.70	3.43	25.80	180	2,400
Summary results						
Total load	10,927.5	16,138.2	97.77	144.99	6,700	11,100
Total sensible duct loss	144.60	2,925.15	1.22	26.00	100	2,340
Total latent duct loss	26.65	931.11	0.27	8.14	0	480
Total duct loss	**171.25**	**3,856.26**	**1.49**	**34.14**	**100**	**2,820**
Total infiltration load	**363.99**	**2,821.31**	**4.94**	**36.89**	**360**	**3,700**

Table 4-30 **Component loss estimates for Florida home 4 (FL-4)**

Component	**Cooling season** (%)		**Typical day** (%)		**Peak hour** (%)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible						
Conduction	2	11	2	10	2	12
Leakage	0	16	0	16	0	16
Added infiltration	1	7	2	11	4	15
Total sensible loss	**4**	**34**	**4**	**37**	**6**	**43**
Latent						
Conduction	0	0	0	0	0	0
Leakage	0	17	1	18	0	18
Added infiltration	7	39	10	56	9	92
Total latent loss	**7**	**56**	**11**	**74**	**9**	**111**
Sensible plus latent loss						
Conduction	1	7	1	7	1	9
Leakage	0	16	0	17	0	16

Added infiltration	*3*	*17*	*5*	*25*	*5*	*33*
Total sensible plus latent loss	***5***	***41***	***7***	***49***	***7***	***59***

Table 4-31 **Delivery and system efficiencies for Florida home 4 (FL-4)**

Component	**Cooling season** (%)	**Typical day** (%)	**Peak hour** (%)
Delivery efficiency			
Sensible	*73*	*74*	*72*
Latent	*83*	*82*	*82*
Total delivery efficiency	***76***	***76***	***75***
System efficiency			
Sensible	*63*	*64*	*55*
Latent	*76*	*75*	*77*
Total system efficiency	***68***	***67***	***60***
Estimated regain (sensible only)	***-13***	***-1***	***-15***

Table 4-32 **Component loads and losses for Florida home 5 (FL-5)**

Load/loss component	**Cooling season** (kWh)		**Typical day** (kWh)		**Peak hour** (Wh)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible load	*6,685.70*	*10,744.7*	*59.95*	*95.01*	*4,800*	*8,500*
Latent load	*3,521.90*	*4,686.80*	*28.15*	*38.43*	*1,500*	*2,100*
Total power	*3,829.80*	*5,875.10*	*35.44*	*54.36*	*2,800*	*4,700*
Conduction losses						
Supply duct sensible	*85.40*	*735.63*	*0.69*	*6.05*	*70*	*610*
Supply duct latent	*6.05*	*3.05*	*0.05*	*0.02*	*0*	*0*
Return duct sensible	*7.14*	*47.60*	*0.05*	*0.36*	*0*	*50*
Return duct latent	*0.57*	*0.24*	*0.00*	*0.00*	*0*	*0*
Leakage losses						
Supply duct sensible	*6.93*	*1,977.45*	*0.06*	*16.73*	*0*	*1,450*
Supply duct latent	*3.67*	*880.41*	*0.03*	*6.89*	*0*	*375*
Return duct sensible	*1.69*	*16.84*	*0.02*	*0.22*	*0*	*50*
Return duct latent	*4.75*	*48.59*	*0.06*	*0.54*	*0*	*50*
Infiltration load						
Sensible infiltration load	*92.25*	*936.14*	*1.42*	*13.44*	*200*	*1,600*
Latent infiltration load	*282.33*	*2,903.71*	*3.39*	*32.18*	*200*	*2,000*
Summary results						
Total load	*10,208*	*15,431.5*	*88.10*	*133.44*	*6,300*	*10,600*
Total sensible duct loss	*101*	*2,777.52*	*0.83*	*23.36*	*70*	*2,160*
Total latent duct loss	*15*	*932.29*	*0.14*	*7.44*	*0*	*425*
Total duct loss	***116***	***3,709.81***	***0.96***	***30.80***	***70***	***2,585***
Total infiltration load	***375***	***3,839.85***	***4.81***	***45.62***	***400***	***3,600***

Table 4-33 **Component loss estimates for Florida home 5 (FL-5)**

Component	**Cooling season** (%)		**Typical day** (%)		**Peak hour** (%)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible						
Conduction	*0*	*7*	*1*	*7*	*1*	*8*
Leakage	*0*	*19*	*0*	*18*	*0*	*18*
Added infiltration	*0*	*9*	*2*	*14*	*4*	*19*
Total sensible loss	***0***	***35***	***4***	***39***	***6***	***44***
Latent						
Conduction	*0*	*0*	*0*	*0*	*0*	*0*
Leakage	*0*	*20*	*0*	*19*	*0*	*20*
Added infiltration	*8*	*62*	*12*	*84*	*13*	*95*
Total latent loss	***8***	***82***	***13***	***103***	***13***	***115***
Sensible plus latent loss						
Conduction	*1*	*5*	*1*	*5*	*1*	*6*
Leakage	*0*	*19*	*0*	*18*	*0*	*18*
Added infiltration	*4*	*25*	*5*	*34*	*6*	*34*
Total sensible plus latent loss	***5***	***49***	***7***	***57***	***7***	***58***

Table 4-34 **Delivery and system efficiencies for Florida home 5 (FL-5)**

Component	**Cooling season** (%)	**Typical day** (%)	**Peak hour** (%)
Delivery efficiency			
Sensible	*74*	*75*	*75*
Latent	*80*	*81*	*80*
Total delivery efficiency	***76***	***77***	***76***
System efficiency			
Sensible	*62*	*63*	*56*
Latent	*75*	*73*	*71*
Total system efficiency	***66***	***66***	***59***
Estimated regain (sensible only)	***-16***	***1***	***-6***

4.5.2. Summary of efficiencies -- Florida Homes

As stated in section 3.2, it is recommended that the sensible efficiencies be considered as the primary indicator of duct system performance followed by the total efficiencies. Accordingly, only the sensible and total efficiencies are summarized here.

Table 4-35 **Sensible efficiencies for Florida homes**

House ID	Sensible delivery efficiency (%)			Sensible system efficiency (%)		
	Season	Typical day	Peak hour	Season	Typical day	Peak hour
FL-1	*79.60*	*79.90*	*77.10*	*76.90*	*75.30*	*70.00*
FL-2	*83.60*	*84.10*	*82.70*	*80.60*	*79.70*	*74.20*
FL-3	*83.30*	*83.60*	*80.40*	*81.80*	*81.20*	*75.80*
FL-4	*72.80*	*73.80*	*72.50*	*63.40*	*63.80*	*55.30*
FL-5	*74.10*	*75.40*	*74.60*	*62.20*	*63.10*	*56.50*

Table 4-36 **Total efficiencies for Florida homes**

House ID	Sensible delivery efficiency (%)			Sensible system efficiency (%)		
	Season	Typical day	Peak hour	Season	Typical day	Peak hour
FL-1	*82.30*	*82.20*	*79.60*	*79.40*	*77.30*	*72.90*
FL-2	*86.50*	*86.60*	*85.10*	*82.90*	*81.30*	*76.00*
FL-3	*86.50*	*86.50*	*83.30*	*84.10*	*82.80*	*78.20*
FL-4	*76.10*	*76.50*	*74.60*	*67.70*	*67.40*	*60.40*
FL-5	*76.00*	*76.90*	*75.60*	*66.10*	*66.00*	*59.40*

For the Florida homes, the sensible delivery efficiencies vary anywhere between 72 to 84 percent indicating a 16-28 percent potential sensible energy loss in the delivery system. The total delivery efficiencies, however, vary between the mid-seventies to mid-eighties. As reflected by the negative values, it appears that ducts located in a hot attic are a liability with regard to regain of the energy lost in the distribution system. When supply air leaks into the attic, it positively pressurizes the attic and de-pressurizes the conditioned zone. Hot attic air is drawn into the room increasing the cooling load. As a result, the system efficiencies are generally lower than the corresponding delivery efficiencies.

Sensible system efficiencies range between 55 to 82 percent indicating that 18 to 45 percent reductions are possible in cooling energy use by attempting to perfect the distribution system. A practical alternative to relocating ducts to the conditioning space is duct sealing and increasing duct insulation levels. It is also important to eliminate pressure gradients between conditioned and buffer zones.

4.6. North Carolina results

Tables in this section present the results of the analysis for the two North Carolina cases. Two of the homes analyzed in the heating section of this report, AL-3 and AL-4 --a single- and a double-section home--were also analyzed in the cooling mode with North Carolina weather data. TMY weather data for Raleigh was used to simulate the cooling season for these homes.

4.6.1. Loads, Losses, penalties for North Carolina Climate

Table 4-37 **Component loads and losses for North Carolina home 1 (NC-1)**

Load/loss component	**Cooling season** (kWh)		**Typical day** (kWh)		**Peak hour** (Wh)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible load	*1,642.27*	*1,876.28*	*36.39*	*43.95*	*3,300*	*4,200*
Latent load	*1,010.30*	*1,180.58*	*19.66*	*24.53*	*1,800*	*1,990*
Total power	*884.31*	*1,025.06*	*20.17*	*24.84*	*1,500*	*2,450*
Conduction losses						
Supply duct sensible	*8.78*	*182.90*	*0.20*	*4.52*	*25*	*450*
Supply duct latent	*0.80*	*0.50*	*0.01*	*0.01*	*0*	*0*
Return closet sensible	*0.21*	*5.83*	*0.00*	*0.09*	*0*	*0*
Return closet latent	*0.13*	*0.06*	*0.00*	*0.00*	*0*	*0*
Leakage losses						
Supply duct sensible	*1.26*	*174.83*	*0.03*	*4.22*	*5*	*400*
Supply duct latent	*0.78*	*117.28*	*0.02*	*2.52*	*5*	*200*
Return closet sensible	*3.14*	*5.43*	*0.12*	*0.23*	*5*	*25*
Return closet latent	*6.20*	*9.92*	*0.17*	*0.28*	*5*	*25*
Infiltration load						
Sensible infiltration load	*26.94*	*88.91*	*1.15*	*4.03*	*165*	*560*
Latent infiltration load	*55.52*	*164.30*	*1.59*	*4.95*	*115*	*375*
Summary results						
Total load	*2,652.57*	*3,056.86*	*56.05*	*68.48*	*5,100*	*6,190*
Total sensible duct loss	*13.39*	*368.99*	*0.35*	*9.06*	*35*	*875*
Total latent duct loss	*7.91*	*127.76*	*0.19*	*2.81*	*10*	*225*
Total duct loss	***21.30***	***496.75***	***0.54***	***11.87***	***45***	***1,100***
Total infiltration load	***82.46***	***253.21***	***2.74***	***8.98***	***280***	***935***

Table 4-38 **Component loss estimates for North Carolina home 1 (NC-1)**

Component	**Cooling season** (%)		**Typical day** (%)		**Peak hour** (%)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible						
Conduction	*1*	*10*	*1*	*10*	*1*	*11*
Leakage	*0*	*10*	*0*	*10*	*0*	*10*
Added infiltration	*2*	*5*	*3*	*9*	*5*	*13*
Total sensible loss	***2***	***24***	***4***	***30***	***6***	***34***
Latent						
Conduction	*0*	*0*	*0*	*0*	*0*	*0*
Leakage	*1*	*11*	*1*	*11*	*1*	*11*
Added infiltration	*5*	*14*	*8*	*20*	*6*	*19*
Total latent loss	***6***	***25***	***9***	***32***	***7***	***30***
Sensible plus latent loss						
Conduction	*0*	*6*	*0*	*7*	*0*	*7*
Leakage	*0*	*10*	*1*	*11*	*0*	*11*
Added infiltration	*3*	*8*	*5*	*13*	*5*	*15*
Total sensible plus latent loss	***4***	***25***	***6***	***30***	***6***	***33***

Table 4-39 **Delivery and system efficiencies for North Carolina home 1 (NC-1)**

Component	**Cooling season** (%)	**Typical day** (%)	**Peak hour** (%)
Delivery efficiency			
Sensible	*80*	*79*	*79*
Latent	*89*	*89*	*89*
Total delivery efficiency	***84***	***83***	***82***
System efficiency			
Sensible	*88*	*83*	*79*
Latent	*86*	*80*	*90*
Total system efficiency	***87***	***82***	***82***
Estimated regain (sensible only)	***53***	***48***	***42***

Table 4-40 **Component loads and losses for North Carolina home 2 (NC-2)**

Load/loss component	**Cooling season** (kWh)		**Typical day** (kWh)		**Peak hour** (Wh)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible load	2,720.94	3,023.81	51.79	62.06	4,100	5,500
Latent load	1,535.01	1,821.18	26.28	34.11	2,500	3,400
Total power	1,502.03	1,719.93	29.82	36.97	1,800	2,500
Conduction losses						
Supply duct sensible	19.06	319.83	0.38	6.89	40	660
Supply duct latent	1.81	0.95	0.03	0.01	0	0
Return closet sensible	0.21	15.77	0.00	0.25	0	25
Return closet latent	0.17	0.07	0.00	0.00	0	0
Leakage losses						
Supply duct sensible	2.75	400.63	0.05	8.17	0	740
Supply duct latent	1.55	243.31	0.02	4.53	0	340
Return closet sensible	0.56	2.36	0.02	0.09	0	10
Return closet latent	1.33	4.97	0.03	0.12	0	10
Infiltration load						
Sensible infiltration load	29.54	131.98	1.26	5.73	175	790
Latent infiltration load	84.41	309.81	2.05	7.99	140	615
Summary results						
Total load	4,255.95	4,844.99	78.07	96.17	6,600	8,900
Total sensible duct loss	22.58	738.59	0.45	15.40	40	1,435
Total latent duct loss	4.86	249.30	0.09	4.67	0	350
Total duct loss	**27.44**	**987.89**	**0.53**	**20.07**	**40**	**1,785**
Total infiltration load	**113.95**	**441.79**	**3.31**	**13.72**	**315**	**1,405**

Table 4-41 **Component loss estimates for North Carolina home 2 (NC-2)**

Component	**Cooling season** (%)		**Typical day** (%)		**Peak hour** (%)	
	Optimum	**Actual**	**Optimum**	**Actual**	**Optimum**	**Actual**
Sensible						
Conduction	1	11	1	12	1	12
Leakage	0	13	0	13	0	14
Added infiltration	1	4	2	9	4	14
Total sensible loss	**2**	**29**	**3**	**34**	**5**	**40**
Latent						
Conduction	0	0	0	0	0	0
Leakage	0	14	0	14	0	10
Added infiltration	5	17	8	23	6	18
Total latent loss	**6**	**31**	**8**	**37**	**6**	**28**
Sensible plus latent loss						
Conduction	0	7	1	7	1	8
Leakage	0	13	0	13	0	12

Added infiltration	*3*	*9*	*4*	*14*	*5*	*16*
Total sensible plus latent loss	***3***	***30***	***5***	***35***	***5***	***36***

Table 4-42 **Delivery and system efficiencies for North Carolina home 2 (NC-2)**

Component	**Cooling season** (%)	**Typical day** (%)	**Peak hour** (%)
Delivery efficiency			
Sensible	*76*	*75*	*74*
Latent	*86*	*86*	*90*
Total delivery efficiency	***80***	***79***	***80***
System efficiency			
Sensible	*90*	*83*	*75*
Latent	*84*	*77*	*74*
Total system efficiency	***88***	***81***	***74***
Estimated regain (sensible only)	***73***	***62***	***45***

4.6.2. Summary and Conclusions -- North Carolina

As stated in section 3.2, it is recommended that the sensible efficiencies be considered as the primary indicator of duct system performance followed by the total efficiencies. Accordingly, only the sensible and total efficiencies are summarized here.

Table 4-43 **Sensible efficiencies for North Carolina homes**

House ID	**Sensible delivery efficiency** (%)			**Sensible system efficiency** (%)		
	Season	**Typical day**	**Peak hour**	**Season**	**Typical day**	**Peak hour**
NC-1	*80.30*	*79.40*	*79.20*	*87.50*	*82.80*	*78.60*
NC-2	*75.60*	*75.20*	*73.90*	*90.00*	*83.50*	*74.50*

Table 4-44 **Total efficiencies for North Carolina homes**

House ID	**Total delivery efficiency** (%)			**Total system efficiency** (%)		
	Season	**Typical day**	**Peak hour**	**Season**	**Typical day**	**Peak hour**
NC-1	*83.70*	*82.70*	*82.20*	*86.80*	*81.80*	*82.40*
NC-2	*79.60*	*79.10*	*79.90*	*87.80*	*81.20*	*74.20*

For North Carolina, the sensible delivery efficiencies vary anywhere between 74 and 80 percent indicating a 20 to 26 percent potential sensible energy loss in the delivery system. The total delivery efficiencies, however, average around 80 percent. Because of positive regain (sometimes called recovery) the system efficiencies are generally higher than the delivery efficiencies. Sensible system efficiencies range between 78 to 90 percent indicating that a 10 to 22 percent improvement is feasible. As in the Alabama, it appears that a portion of the duct loss is recovered back in the conditioned zone.

4.7. Discussion and conclusions

The preceding sections presented the results of analysis of twelve homes in Alabama, Florida and North Carolina. The results of the analysis indicate that in the homes analyzed the energy lost in delivery is in the range of 10 to 30 percent. However, the results also clearly indicate that location of the supply ducts has a bearing on whether the energy lost in delivery is recovered (at least partially) or an additional penalty is imposed on cooling system performance. The graphs that follow (Figures 4-5 through 4-8) illustrate the point by comparing an *actual* and *optimum* home in Alabama and Florida on a typical summer day.

Each figure contains five plots describing the behavior of the homes as indicated below:

PLOT a:	shows the zone temperatures for the home, including living, attic, belly and ambient
PLOT b:	shows the sensible load, latent load and cooling system power consumption
PLOT c:	shows the relative humidities for the living zone, attic, belly and ambient
PLOT d:	shows the energy lost in the duct system due to sensible and latent conduction
PLOT e:	shows the energy lost in the duct system due to leakage
PLOT f:	shows the sensible and latent loads due to forced infiltration because of system operation.

Due to supply air leakage and conduction losses, the belly temperatures for the Alabama homes are generally lower than the living zone for the *actual* configuration (Plot a in Figure 4-5), and generally higher than the living zone temperature in the *optimum* configuration (Plot a in Figures 4-6). The floor, therefore, acts as a sink in the *actual* configuration and as a heat source in the *optimum* configuration, contributing to regain of energy lost due to conduction and leakage in the duct system. Thus when ducts are placed in the belly, it appears that an increasing leakage will contribute to lower conductive losses, and any potential costs and savings due to repairing duct leaks must be viewed in this light.

On the other hand, for Florida homes, placing ducts in the attic produces a more pronounced penalty. The attic temperatures (Plot a in Figures 4-7 and 4-8) are always substantially higher than the living zone. When supply air leaks into the attic, it positively pressurizes the attic and de-pressurizes the conditioned zone.

Hot attic air is drawn into the room placing an additional load on the building. Supply leaks in the attic, therefore, impose a two-fold penalty on the cooling energy use if the ceiling plane between the attic and living zones is not tightly sealed. Further, it is evident that an optimum duct system will tend to maintain lower indoor humidities (Plots c, in Figures 4-5 and 4-6) -- a factor important in hot-humid climates -- and can lead to better comfort.

In addition, there is the additional penalty due to added forced infiltration when supply leaks occur in the ducts. In many instances, the latent penalty due to increased whole house infiltration is more than the corresponding sensible component (Plot f, in Figures 4-5 and 4-7).

Delivery losses in Alabama are in the range of 12 to 30 percent, while in Florida it is in the range of 20 to 30 percent. The distribution system penalty, which indicates the possible reductions in cooling loads, is in the 10 to 25 percent range in Alabama, while in Florida it is in the range of 15 to 45 percent. Delivery and system efficiencies for all homes are summarized in the two tables below.

Table 4-45 **Sensible efficiencies for all homes**

House ID	**Sensible delivery efficiency** (%)			**Sensible system efficiency** (%)		
	Season	**Typical day**	**Peak hour**	**Season**	**Typical day**	**Peak hour**
AL-1	*81.30*	*81.30*	*80.60*	*87.00*	*84.10*	*78.10*
AL-2	*71.60*	*73.00*	*72.20*	*92.70*	*88.20*	*84.80*
AL-3	*80.20*	*79.50*	*79.20*	*86.40*	*80.50*	*73.30*
AL-4	*75.50*	*75.00*	*74.30*	*88.30*	*80.20*	*75.00*
AL-5	*73.20*	*72.90*	*72.50*	*85.40*	*79.70*	*78.20*
FL-1	*79.60*	*79.90*	*77.10*	*76.90*	*75.30*	*70.00*
FL-2	*83.60*	*84.10*	*82.70*	*80.60*	*79.70*	*74.20*
FL-3	*83.30*	*83.60*	*80.40*	*81.80*	*81.20*	*75.80*
FL-4	*72.80*	*73.80*	*72.50*	*63.40*	*63.80*	*55.30*
FL-5	*74.10*	*75.40*	*74.60*	*62.20*	*63.10*	*56.50*
NC-1	*80.30*	*79.40*	*79.20*	*87.50*	*82.80*	*78.60*
NC-2	*75.60*	*75.20*	*73.60*	*90.00*	*83.50*	*74.50*

Table 4-46 **Total efficiencies for all homes**

House ID	**Total delivery efficiency** (%)			**Total system efficiency** (%)		
	Season	**Typical day**	**Peak hour**	**Season**	**Typical day**	**Peak hour**
AL-1	*83.80*	*83.50*	*82.00*	*85.00*	*82.60*	*77.30*
AL-2	*74.30*	*76.30*	*74.90*	*90.50*	*86.40*	*83.20*
AL-3	*83.70*	*82.80*	*81.90*	*85.30*	*79.70*	*73.20*
AL-4	*79.80*	*79.20*	*78.20*	*85.60*	*78.10*	*74.30*
AL-5	*78.60*	*78.20*	*77.20*	*83.90*	*78.30*	*76.20*
FL-1	*82.30*	*82.20*	*79.60*	*79.40*	*77.30*	*72.90*
FL-2	*86.50*	*86.60*	*85.10*	*82.90*	*81.30*	*76.00*
FL-3	*86.50*	*86.50*	*83.30*	*84.10*	*82.80*	*78.20*
FL-4	*76.10*	*76.50*	*74.60*	*67.70*	*67.40*	*60.40*

FL-5	*76.00*	*76.90*	*75.60*	*66.10*	*66.00*	*57.40*
NC-1	*83.70*	*82.70*	*82.20*	*86.80*	*81.80*	*82.40*
NC-2	*79.60*	*79.10*	*79.90*	*87.80*	*81.20*	*74.20*

Figure 4-5 **Alabama house 4 (AL-4) - Typical summer day, actual configuration**

Figure 4-6 **Alabama house 4 (AL-4) - Typical summer day, optimum configuration**

Figure 4-7 **Florida house 3 (FL-3) - Typical summer day, actual configuration**

Figure 4-8 **Florida house 3 (FL-3) - Typical summer day, optimum configuration**

5. Annotated Literature Review

1. *Home Energy* magazine, 1993, ***Special Issue: Ducts Rediscovered***, Volume 10, Number 5, September/October 1993

Study objective: In this issue, *Home Energy* magazine presented a series of articles on ducts offering an overview of the subject area. The articles are intended as a primer for building professionals.

Relevant findings: The articles that fill this special issue on duct systems do not shed new light on duct performance but rather form a useful composite picture of our current knowledge in the area. Many of the research concepts and principles discussed in the other papers reviewed in the literature review are summarized in the *Home Energy* articles. The articles dealing with testing methods and the performance of sealant materials are the most applicable to the current manufactured housing study.

Implications for the AEC study: Like the majority of articles in the literature, the *Home Energy* issue emphasizes site-built duct systems. Much of what is contained in these articles has little direct bearing on manufactured housing.

2. Olson, Joseph R.; L. Palmiter; B. Davis; M. Geffon; and T. Bond, 1993, **Field measurements of the heating efficiency of electric forced-air systems in 24 homes**, Residential Construction: Demonstration Cycle III, Portland, OR: Bonneville Power Administration

Study objective: Field study of 24 site-built homes to determine heating efficiency of electrically-heated homes with duct distribution expressed in terms of overall heat delivery and system efficiency.

Relevant findings: Twenty-two of the 24 homes in the sample had ducts in unconditioned spaces. The other two homes had the equipment and distribution system within the conditioned envelope. The latter two homes had a heating system efficiency of 98 percent indicating that almost all of the duct losses were recovered as useful heat. Average system efficiency of the other 22 homes was 71 percent suggesting that a ducted design consumes 1.41 times as much energy as a non-ducted one. Duct leakage accounted for a major part of the efficiency losses in homes equipped with exterior ductwork (20 percent of the entire home leakage rate).

Implications for the AEC study: While the study findings suggest that ducts can be major contributors to overall energy use and system efficiency, the findings have limited application to multi-section manufactured homes where short external ducts runs are common. Performance of manufactured home distribution systems are likely to fall between the two cases investigated (interior and exterior ducts) because interior ducts in manufactured homes are less isolated from the envelope components than interior ducts in site built homes. This is one of several studies that noted the interrelationship between blower fan operation and whole house infiltration rate.

3. Modera, M.; D. Dickerhoff; R. Jansky; and B. Smith, 1992, ***Improving the efficiency of residential air-distribution systems in California: Phase 1***, *CIEE Research Report Series 5*. Berkeley, CA: California Institute for Energy Efficiency

Study objective: Improve the performance of air distribution systems in site-built homes built in California. Calibrate an algorithm in DOE-2 that predict home and duct air flow and leakage relationships.

Relevant findings: With the emphasis on retrofitting and site-built homes, the study is of limited application to the manufactured housing program. One interesting observation was distribution fan operation increased average infiltration rates from 0.25 to 0.69 ACH as measured by tracer gas techniques. Also, the ducts were estimated to reduce system performance by between 25 and 40 percent. The Uo-value of the thermal envelope, an overall measure of envelope thermal integrity, did not significantly impact results.

Implications for AEC study: Two aspects of the LBL study findings are worth considering in the AEC planning. First, the study indicated a profound correlation between fan operation and infiltration rates. When the fan was activated the ACH rate doubled. Second, there was a direct correspondence noted between air distribution losses and peak demand. Distribution system inefficiencies were estimated to increase cooling peak demand between 1 and 2 kW per home. Cooling peak consumption was predicted to rise as much as 40 percent.

4. GEOMET Technologies, Inc., 1992, ***Residential duct system performance evaluation literature review***, *Final report: Research project 2417-18,* Palo Alto, CA: Electric Power Research Institute

Study objective: Review and summarize published papers dealing with air leakage from residential duct systems and evaluate methods for detecting leaks.

Relevant findings: This paper is a literature review narrowly focused on residential duct leakage causes, detection, and measurement. In the introductory paragraph, the authors note that air infiltration rates increase 30 to 70 percent when the blower fan is activated. Also mentioned are the potential deleterious impacts of leakage into and out of the ducts. These might include increased energy use and peak demand, the latter rising by as much as 4 kW in hot, humid climates. Comfort is also compromised due to a temperature drop between the furnace and outlet and inability to control humidity levels. The report argues that repairs are relatively easy to make and are cost-effective. The study concluded that the method for measuring duct leakage should be dependent on the objectives or intended use of the measurement results. As an appropriate standard test method, the flow hood method described by Modera (1990) in the ASTM standard is suggested.

Implications for the AEC study: The literature search mainly contains citations of site-built duct leakage testing and test results. However, the suggested relationship between study objective and test method (illustrated on the table below) is transferable to the current work.

Objective	Test Method
Qualify leakage from relatively leaky ducts Diagnostic and post-repair assessments	**Blower door**
More accurate measurement of supply/return duct leakage Inter-building comparison Diagnostic and post-repair assessments	**Flow Hood**
Measure air exchange rate due to fan operation Energy and indoor air quality impact	**Tracer gas**

5. Andrews, John W.; and M. P. Modera, 1992, ***Thermal distribution in small buildings: A review and analysis of recent literature***, Upton, NY: Brookhaven National Laboratory

Study objective: Review the literature related to energy losses in ductwork and the potential energy savings associated with zone control.

Relevant findings: Energy losses were found to be primarily related to three phenomena: fan-induced infiltration, duct leakage, and conductive losses. On average, duct systems were found to be between 60 and 70 percent efficient. The literature search also summarized the prospects for reducing energy use through zone control. This study characterized the areas of energy loss associated with duct systems and compared the findings of several studies. For example, seven studies were compared in which whole house air leakage attributable to ducts was measured. The associated increase in air leakage averaged about 14 percent with a range in values of 10 to 17 percent.

Implications for the AEC study: This paper is a valuable resource from the standpoint of providing a model for understanding and characterizing how ducts influence energy use and in quantifying their relative importance. The comparison amongst studies is interesting, although the authors had relatively few contemporary studies to compare. While the technique for compartmentalizing the loss mechanisms is transferable to manufactured homes, with a few exceptions, the findings with regard to the size of each are probably not applicable to the current study.

6. Modera, Mark P.; Andrews, J. W.; and, Kweller, Esher, ***A comprehensive yardstick for residential thermal distribution efficiency***, Upton, NY: Brookhaven National Laboratory

Study objective: Describe a framework for a figure of merit, a rating system by which the energy performance of distribution systems can be compared.

Relevant findings: This is a rather ambitious attempt to express in a single measure the overall performance of the duct system on energy use.

Implications for the AEC study: The application of the method to manufactured housing requires further study. However, the authors have suggested a useful categorization of air distribution loss mechanisms that can be applied to the current work. The categories are listed below.

- **Thermal distribution interactions with heating and/or cooling equipment**
    - Dependence of distribution systems on equipment type, sizing, and operating mode
    - System cycling interactions
    - Impacts of fluid transport temperature and medium on equipment heat exchanger and efficiency
    - Impacts of variable capacity equipment and fans

- **Thermal distribution interactions with the building envelope during system operation**
    - Impacts of duct leakage on infiltration rates and locations
    - Impacts of imbalanced air flows on infiltration rates and locations
    - Impacts of leakage and conduction losses to unconditioned spaces
    - Impacts of zoning on envelope and internal wall design
    - Impact of radiant/convective split on thermostat set points

- **Thermal distribution interactions with the building envelope during off-cycle periods**
    - Impacts of duct leakage on whole house infiltration rates
    - Impacts of continuous fan operation on infiltration and conduction losses
    - Thermal bridge and thermal siphon effects of poorly insulated ducts in unconditioned spaces
    - Hydronic-system losses during off-cycle periods

- **Non-interactive Issues**
    - Impacts of system design and fan energy losses
    - Location of air distribution system (conditioned versus unconditioned spaces)
    - Weather pattern impacts

These categories work equally well for manufactured housing and other small building types. The authors describe quantitative procedures that take into consideration the cumulative impact of the issues described above. (The reference point for comparison is a building of identical features that has no thermal distribution losses.) However, the relative importance of these loss factors is established only for site built and likely to be different for manufactured homes. Despite this limitation, the concept of creating a single reference point for measuring the overall efficiency of any configuration of distribution system is compelling and merits serious consideration as an evaluative tool in the present study.

7. Andrews, John W., editor, 1992, ***Proceedings of the 1992 DOE-industry thermal distribution conference***, Upton, NY: Brookhaven National Laboratory

Study objective: This document summarizes the results of a conference on thermal distribution systems held in 1992.

Relevant findings: The conference attempted to create consensus as to the thermal distribution research areas that DOE should consider funding. The proceedings provide an overview of the state of knowledge in air distribution systems, with emphasis on site-built homes. In addition to the papers, the conference contained four panel sessions exploring R&D needs in the areas of codes and standards, DSM programs, retrofit applications, and marketing. The panels reached consensus or near consensus on the need to conduct research in four areas: AFUE-like figure of merit; education and training; stock characterization; and, design guidelines.

Implications for the AEC study: The broad findings of the conference have application to the current study, although most of the specifics do not translate well to manufactured homes. One of the categories of comments worth repeating dealt with home builder motivation (or lack of interest) in voluntarily changing duct installation methods. The proceedings suggested that there is little incentive for builders to lavish more attention on ducts. The authors note that the *"system is geared toward minimizing callbacks, not maximizing energy efficiency. For this system to work, a large margin of error is needed in the system design; this is usually achieved by oversizing the primary equipment."* The observation also applies to manufactured housing.

8. Judkoff, Ronald; and Gregory Barket, 1992, ***Thermal testing of the proposed HUD energy efficiency standard for new manufactured homes***, Golden, CO: National Renewable Energy Laboratory

Study objective: Measure the performance of two homes built to the proposed HUD standards of 1993.

Relevant findings: Exploration of duct loss impacts was a small part of this study that sought to evaluate the potential impacts of changes to the energy standards for manufactured homes. Specifically, with regard to the air distribution system, Duct Blaster™ tests were conducted to quantify the impact of leaks in the ducts with and without holes in the rodent barrier (bottom board). Tests were performed by Florida Solar Energy Center. The findings were summarized as follows: (1) duct leakage in the homes was small; (2) after punching three holes in the rodent barrier, duct leakage changed only slightly; and, (3) there were pressure imbalances of about 4 pascals between the living spaces and outside of the home when the furnace blower was operating and interior doors closed.

Implications for the AEC study: Despite the limited coverage afforded the air distribution system by the NREL researchers, the study raises important questions about the tightness of ducts in new manufactured homes. Along with several other studies, the NREL researchers conclude that manufactured homes are underventilated. The sample size is too small to suggest any broad generalizations. However, safety and health may be negatively impacted by a 4 pascal pressure difference. As a result, it may be wise to obtain additional measurements in this area for homes containing combustion appliances.

9. Tecogen, Inc., 1990, ***Heat pump thermal distribution systems, Volume I: Systems analyses***, *Final report: Research project CU-6962*, Palo Alto, CA: Electric Power Research Institute

Study objective: Identify the lowest cost residential thermal distribution system (air, liquid, and refrigerant) and the most competitive method for heat pump zoning using this system.

Relevant findings: Among the limitations of this study relative to the AEC project are the emphasis on distribution systems for use with heat pumps and application to site-built homes. These factors aside, the study concluded that a new type of ductwork, rectangular flexible duct, was promising for single-zoned heat pump installations. It proved to be less expensive than rectangular ducts although more costly than round flex-duct. This result is likely to be limited to site-built homes. For two or more zones, an air-to-water hydronic system was shown to be cost-efficient. Refrigerant-based distribution systems were too expensive to be justified in small buildings.

Implications for the AEC study: By concentrating on heat pump systems and cost parameters for site-built housing, neither of which have much application to manufactured housing, the study is of little direct value for the AEC study. However, the concept that the best thermal distribution system may be a function of the equipment type merits consideration. The study also introduces the idea that cost-effectiveness be considered over a sufficiently long time horizon to reflect energy cost savings benefits.

10. Andrews, John W; and, Mark Modera, 1991, ***Energy savings potential for advanced thermal distribution technology in residential and small commercial structures (draft)***, Upton, NY: Brookhaven National Laboratory

Study objective: Assess the energy saving potential of improved distribution systems.

Relevant findings: This study attempted to quantify the impact on national energy use of selective changes to the distribution system. Savings estimates were derived for various distribution system types and building configurations. However, because of the methods used in the study, HUD-code homes were explicitly eliminated from the computations. The total family of HUD-code units was estimated at 5.1 million of which 3.9 million are assumed to be forced-air. These are probably underestimates since the values were derived from the Residential Energy Consumption Survey (RECS), a study that uses a small manufactured housing sample size.

Implications for the AEC study: Projecting energy savings due to particular technologies is a difficult business. There is often a tendency to overestimate savings by placing more emphasis on the particular technology in question than can be expected in the real world. However, some measure of potential is useful and the procedures used by the authors can be applied to manufactured housing if justified in the current work.

11. Proctor, John, 1990, ***Pacific Gas and Electric Appliance Doctor Pilot Project,*** *Final report: summer 1990 activity*, San Francisco, CA: Proctor Engineering Group

Study objective: Investigate the potential for energy use reduction in existing HVAC systems in Fresno, CA.

Relevant findings: A fifteen-home study was undertaken to determine what kinds of residential retrofit measures would yield significant benefits for homes in PG&E service territory. A team visited each home to test and repair HVAC equipment and duct systems. Duct leakage was the largest problem in the homes studied. Average leakage at 50 pascals as measured by duct subtraction was 419 cfm accounting for about 15 percent of the total home leakage area. However, leakage in the duct system was noted as being more critical than leaks in the thermal envelope. The ducts experience a higher pressure differential across the duct wall, a higher temperature difference between the duct air and ambient, and duct leakage tends to increase the rate of furnace cycling. The study noted that losses due to duct leakage increased cooling loads by about 25 percent and heating loads by 16 percent. Technicians were able to seal about 60 percent of the leaks. Many of the leakage locations were inaccessible. Duct sealing in this instance had little impact on the equipment input energy requirements. However, the coincident peak dropped by 527 watts.

Implications for the AEC study: This study, rather than introducing new or different findings, corroborated the observations offered by other studies. The specific data gathered from site-built homes with high bill complaints (i.e., magnitude of losses and percentages), cannot be generalized to manufactured homes.

12. Robison, D. H.; and L. A. Lambert, 1989 , ***Field investigation of residential infiltration and heating duct leakage***, *ASHRAE Transactions*, Volume 95, Part 2, Atlanta, GA

Study objective: Quantify the level of duct leakage in conventional housing and estimate the impact of retrofit measures on energy use.

Relevant findings: Homes selected for analysis were all site-built and part of the BPA Residential Standards Demonstration Program. There was a high variability in leakage levels. About 10 percent were considered tight and an equal percent very leaky. Retrofit procedures were able to reduce loses by about 20 percent. Energy loses in overall system efficiency due to leakage were estimated at 12 percent.

Implications for AEC study: This study has limited application to manufactured homes because it examined site built homes and attempted to quantify the impact of retrofit measures. One interesting observation was the difficulty in repairing poorly installed ducts, a strong argument for proper initial installation.

13. The Fleming Group, 1989, ***Evaluation of energy conservation measures for mobile homes***, *Final report,* Albany, NY: New York State Energy Research and Development Authority
Kinney, Larry; G. Klein; J. A. Morine; D. B. Sherman; and, M. A. White, 1987, ***Appendix A* (unpublished), *Blower door measurements on manufactured homes,*** Syracuse, NY: New York State Energy Research and Development Authority.

Study objective: Assess the potential for reducing air infiltration rates in existing manufactured homes.

Relevant findings: The study, limited to counties in upstate New York, suggests that, while existing homes present a wide range of air leakage rates, very loose homes appear to be the rule rather than the exception. The thrust of the analysis dealt with whole house infiltration, although of the 50 homes tested, about 20 percent were characterized as tight, 60 percent as leaky, and 20 percent as very leaky. While no attempt was made to repair leaky ducts, the authors noted that repairing ducts can yield greater benefits than other kinds of infiltration reducing strategies.

Implications for the AEC study: The report by Synertech generally supports the need for the AEC work without providing data specific to duct leakage losses. The authors observed that existing home duct systems can be a serious site for leakage.

14. Herold, K. E.; R. D. Fischer; and L. J. Flanigan, 1987, ***Measured cooling performance of central forced-air systems and validation of the SP43 simulation model***, *ASHRAE Transactions, Vol. 93, Part 1,* Atlanta, GA
Jakob, F. E.; R. D. Fischer; and L. J. Flanigan, 1987, ***Experimental validation of the duct submodel for the SP43 simulation model***, *ASHRAE Transactions, Vol. 93, Part 1,* Atlanta, GA
Jacob, F. E.; R. D. Fischer; L. J. Flanigan; D. W. Locklin; K. E. Herold; and R. A. Cudnik, 1986, ***Validation of the ASHRAE SP43 dynamic simulation model for residential forced warm-air systems***, *ASHRAE Transactions, Vol. 92, Part 2,* Atlanta, GA
Jacob, F. E.; D. W. Locklin; R. D. Fischer; L. J. Flanigan; and R. A. Cudnik, 1986, ***SP43 evaluation of system options for residential forced-air heating,*** *ASHRAE Transactions, Vol. 92, Part 2,* Atlanta, GA
Fischer, R. D.; F. E. Jakob; L. J. Flanigan; D. W. Locklin; and R. A. Cudnik, 1984, ***Dynamic performance of residential warm-air heating systems -* Status of ASHRAE Project SP43***, *ASHRAE Transactions, Vol. 90, Part 2,* Atlanta, GA

Study objective: These reports constitute a series of papers describing the work of SP43 in developing a model that can simulate residential duct performance. Overall goals are to provide information for the ASHRAE Handbook on seasonal performance and energy use, and refine existing duct test procedures for evaluation of seasonal energy use. Andrews (16) noted that SP43 had two major accomplishments. First, it developed a consistent methodology for quantifying the interactions of the duct system with the furnace and building envelope. Second, it allowed the relative impacts of various approaches to system improvement to be quantified.

Relevant findings: SP43 selected an existing computer model and made a series of refinements to allow it to emulate the dynamic performance of ducted systems. The model incorporates the following parameters: house design, furnace features, air distribution system, venting system, infiltration and exfiltration, and controls. The validation was accomplished using two site-built homes with basements heated with gas furnaces. This validation work suggested that improvements in the duct system would yield small benefits since the losses were heating the basement space reducing the temperature difference between the basement and the living spaces. The studies also revealed that the leakier the ducts the higher the supply register temperature since this results in longer on-time of the equipment. The authors note that external ducts benefit "dramatically" from insulation upgrades and sealing. Some other interesting findings of the SP43 program include the following: there was no energy penalty for oversizing the furnace although there is a comfort penalty due to larger temperature swings; running the blower fan continuously engenders an energy cost but provides more comfortable internal conditions (this may be even more the case with manufactured homes); and generally the interactions between equipment size and efficiency, duct system design and installation, and factors such as infiltration rate can significantly impact overall performance. For example, in one case, almost half of the heat delivered to the living space came from equipment losses, resulting in a very low system efficiency. Since the system losses partially offset space conditioning needs, the furnace operated less (fewer cycles, longer off-time) and duct efficiency suffered. This case, as it turns out, was the most energy efficient once credit was given for losses that translate into miscellaneous gains.

Implications for the AEC study: The model has potential use in the AEC study. In addition, the work of SP43 highlights the need to evaluate air distribution performance as one part of a larger system and to develop performance evaluators accordingly. Improving the efficacy of the air distribution system may result in up or down-stream inefficiencies that adversely impact comfort and/or energy use and peak loading.

15. Andrews, J. W., 1986, ***Zoned backup in electric-powered heat pump systems, a way to conserve energy and reduce utility power peak***, Upton, NY: Brookhaven National Laboratory

Study objective: Describe a method for improving the performance of heat pump systems using in-duct resistance heaters.

Relevant findings: This brief paper explored the use of a technology that would reduce energy use and peak loads in buildings with heat pumps. The authors suggest placing small resistance heaters within the duct itself that can be activated by thermostats in the individual rooms of the home. This would reduce duct losses since the heating source would be much closer to the space to be heated. Wiring for the resistance heaters would run through the ductwork. Preliminary estimates of savings for a case study city (Albany, NY) are as follows: 43 percent reduction in resistance heating needs; 17 percent reduction in duct losses; 14 percent reduction in total purchased power; and, 32 percent reduction in utility peak load.

Implications for the AEC study: While the concept may be controversial and the details of the design questionable for manufactured housing, it is an interesting way to improve duct performance (i. e., take the ducts off-line during peak usage periods). The approach merits further examination.

16. Andrews, J. W.; B. H. Fleck; R. F. Krajewski; and R. J. McDonald, 1985, ***Thermal distribution and utilization: An interim progress report***, Upton, NY: Brookhaven National Laboratory

Study objective: Summarize the work-to-date (February 1985) in the area of thermal distribution conducted by Brookhaven National Laboratory and the plan for subsequent year research.

Relevant findings: As a plan of action, this document offered little of direct value to the AEC study. This report was followed by a more comprehensive study (see below) that followed up on the recommendations and contained some useful data. However, the BNL reports offer a structure for approaching air distribution research and cataloging results

Implications for the AEC study: This report suggests a strategy for approaching air distribution research generally, although some of the examples pertain mainly to site-built homes. There are some interesting issues raised, such as the most effective ways to represent overall system efficiency. However, specificity is missing. Subsequent studies in this series are of greater interest in this regard.

17. Andrews, J. W.; and R. F. Krajewski, 1985, ***Forced-air thermal distribution systems in small buildings: R&D planning studies in zoning and system losses***, Upton, NY: Brookhaven National Laboratory

Study objective: Characterize the state of knowledge on forced-air distribution systems, zoning of forced-air systems, and hydronic systems in residential buildings.

Relevant findings: This work, now nine years old, takes a snapshot view of distribution systems used in light construction, with an emphasis on housing. The results were used to develop a comprehensive research and development program. The authors noted that there is little published work in this area, a situation that has not appreciably changed in the intervening years. Literature was divided into three areas as follows: (1) measurement of distribution losses; (2) modeling of system performance; and, (3) duct design guidelines. The results of this survey indicated losses due to ducts ranging from five to 50 percent of the furnace output. Only one of the referenced studies examined manufactured homes (Goldschmidt). In addition, authors suggest that zoning strategies can lead to an impressive 25 to 30 percent reduction in total fuel consumed.

Implications for the AEC study: The report suggested methods for structuring the results of the literature search that may be useful in assessing the information contained in this task 1 document. For example, thermal losses were found to be characterized as either Direct or Indirect. Direct losses include duct leakage (convection) and conductive heat transfer through duct walls. Indirect losses include induced infiltration (pressure imbalances), furnace-efficiency impacts, and system imbalances. The relative impact of each of these effects is estimated based on the literature search and methods for reducing impacts similarly identified. Unfortunately, the estimates mainly pertain to site-built homes and may have little relevance to this work.

18. Grot, A. R.; and David T. Harrje, 1981, ***The transient performance of a forced warm air duct system***, *ASHRAE Transactions*

Study objective: Investigate the transient performance of duct systems through experiment and theoretical analysis.

Relevant findings: This is an older study that assessed the value of adding insulation to uninsulated ducts. In the uninsulated state, ducts were found to lose 50 percent of the transported heat through conduction. Performance was improved by insulating the ducts, preferably on the inside, and downsizing the equipment to minimize on-off cycling.

Implications for AEC study: The results of the study were based on field testing of two townhouses in New Jersey. While the findings have general application to any housing type, there is little specific relevance of the findings to the AEC study.

19. Orlando, Joseph A.; M. G. Gamze; N. Malik; R. Crews; G. Michaels; and J. Christie, 1980, ***Analysis of residential duct losses***, Chicago, IL: Gas Research Institute.

Study objective: Investigate ways to improve the efficiency of gas-fired systems in residential buildings with specific emphasis on measuring the performance of distribution systems and identifying ways to improve system performance.

Relevant findings: This study considered myriad ways in which the distribution system can impact energy use. The important loss mechanisms included the following: excess furnace use due to unbalanced air distribution; convective losses due to leaks in the distribution system; decreased furnace efficiency due to inadequate flow of air into the furnace; and, increased air infiltration to meet combustion air requirements. The combined effects of these four loss factors can increase energy use by as much as 40 percent, or, in tighter systems, by as little as 12 percent.

Implications for the AEC study: This was an early yet comprehensive study of the impact of duct losses on total system performance. The findings were based on a limited sample of site-built homes and the authors down-played the ability to extrapolate results to a wider family of homes. The study is notable for the depth of testing and analysis that support the conclusions. Because of the vintage of the study and the fact that the homes were site-built, the results should only be considered broadly illustrative of distribution system weaknesses.

20. Science Applications, Inc., 1979, ***Test report: Mobile home heating, cooling, and fuel burning systems***, *Mobile home research*, Washington, DC.:, U. S. Department of Housing and Urban Development.

Study objective: Conduct testing of manufactured homes to support changes to the HUD standards.

Relevant findings: Two homes were tested in New York State to determine their compliance under the HUD standards and evaluate the efficacy of possible changes in the standards. With regard to duct systems, several observations were made by the authors of the tests. First, ducts were found to leak up to 20 percent at which point they met the static pressure levels specified in the HUD standards. The combination of leakage and thermal losses amounted to 15 percent of the total input energy for the single section home and 22 percent for the multi-section unit. (Testing was done using a Duct Blaster™.) Despite careful field installation, the multi-section home did not meet the air tightness requirements of the standard. Duct registers were determined to be awkwardly and illogically placed with regard to space planning. Imbalances in distribution were noted resulting in large temperature fluctuations in some rooms, particularly in the bathrooms. The appreciable temperature gradients from floor to ceiling suggest that the registers are poorly located. Although the tests were performed in 1979, the problems noted are common to air distribution system of recent vintage.

Implications for the AEC study: The HUD sponsored study is 15 years old but it is still one of the few where tests were performed on manufactured homes. Duct systems have not changed much in the intervening years and the observations are still relevant.