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Reducing Thermal Losses and Gains With Buried and Encapsulated Ducts in Hot-Humid Climates

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Consortium for Advanced Residential Buildings

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Definitions

ACCA	Air Conditioning Contractors of America
ACEEE	American Council for an Energy-Efficient Economy
ACH_{50}	Air changes per hour at 50 Pascal
AHU	Air-handling unit
Apparent R-value	R-value of ductwork including heat transfer between the duct and conditioned space
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CARB	Consortium for Advanced Residential Buildings
ccSPF	Closed-cell polyurethane spray foam
CDD_{75}	Cooling degree days at base 75°F
CEC	California Energy Commission
cfm	Cubic foot per minute
DE	Delivery effectiveness
DOE	U.S. Department of Energy
dof	Degrees of freedom
DSE	Distribution system efficiency
Effective R-value	R-value of ductwork excluding heat transfer between the duct and conditioned space
EIA	Energy Information Administration
HDD_{65}	Heating degree days at base 65°F
ICC	International Code Council
kW	Kilowatt
kWh	Kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LMTD	Log mean temperature difference
NCDC	National Climactic Data Center
NREL	National Renewable Energy Laboratory
Pa	Pascal

Executive Summary

Thermal losses and gains from ductwork installed in unconditioned spaces—such as attics, crawl spaces, and garages—can contribute significantly to the overall heating and cooling loads of single-family residential buildings, with estimated duct losses ranging from 10%–45 %.[1] The impact is particularly severe in hot climates where air conditioning dominates and extensive duct systems are typically located in hot attics. The duct system inefficiencies are greatest at peak demand conditions when the attic is hottest and run times are the highest. The thermal losses and gains at the three single-story houses in Florida monitored in this study accounted for 15%–35% of the annual pre-retrofit heating and cooling energy use and 6%–25% of the total pre-retrofit annual utility bill.

Even though a number of existing methods can effectively move ducts into the conditioned space, they are not currently being widely implemented. Physically locating the ducts within the conditioned space is most often applicable only to new construction projects and requires planning during design. Attics can be insulated at the roof deck with closed-cell polyurethane foam (ccSPF) to reduce duct losses and infiltration rates, but this method has high up-front costs and the potential to increase loads on the building enclosure. In hot-dry climates, attic duct systems can be buried under loose-fill insulation at a significantly lower cost to reduce thermal loads. In hot-humid climates, however, condensation on the duct jacket can occur when the humidity in the attic is high.

Figure 1. Traditional ductwork hung from attic rafters

Figure 2. Ducts being encapsulated with ccSPF

There are almost 3.9 million houses in Florida alone (U.S. Department of Commerce 2003), most with ducts located in vented attics (Figure 1). A feasible and cost-effective retrofit strategy is needed to reduce duct losses in existing homes in hot-humid climates. Through past research, the Consortium for Advanced Residential Buildings has demonstrated the benefits of buried ducts and buried and encapsulated ducts in new construction applications. The buried and encapsulated duct strategy, which utilizes ccSPF to address condensation concerns (Figure 2), was developed specifically for hot-humid climates.

Buried and encapsulated ducts have the potential to substantially improve the thermal performance of existing ductwork and reduce duct air leakage rates. A second variation of the

[1] The range cited here is based on an extensive literature review described further in Section 1.

concept, just encapsulating the ducts without burying them, evolved during this research in response to site constraints. Encapsulating the ducts without burying them beneath loose-fill insulation results in a lower duct R-value, but the trade-offs are lower up-front costs and additional advantages in coordination and installation.

To evaluate the buried duct concept in a retrofit scenario for a hot-humid climate, encapsulated and buried and encapsulated ducts were installed and their performance was monitored in three Jacksonville homes. Ease of installation was also examined as a key factor in this study. Encapsulating ductwork in ccSPF increased the thermal resistance of the existing ductwork and decreased duct leakage rates. Burying these encapsulated ducts beneath loose-fill insulation further increased the R-value of the encapsulated ductwork.

A multifaceted approach—field monitoring, computer modeling and simulation, and numerical analysis—was used to develop a comprehensive view of encapsulated and buried and encapsulated ducts. The primary goals were to quantify the associated energy savings, cost effectiveness, and condensation potential of this retrofit measure. To calculate energy savings and condensation potential, the researchers performed computer modeling and analysis. Data from field testing were used to validate these conclusions and determine cost effectiveness.

This report begins with a comprehensive overview of the buried duct research that has been conducted to date, including the analysis approaches used to support previous research (Sections 1 and 2). In Section 3, detailed information is presented on the retrofit methodology used to install and test the three existing duct systems, including short- and long-term data collection. Section 4 evaluates the retrofit methodology.

After the methods used to retrofit the systems are explained, Section 5 summarizes the results of the field evaluation. The performance testing results are given, and the thermal performance and condensation potential of buried ducts are discussed qualitatively using the data collected during the monitoring period. Changes in the mechanical and distribution system configuration and operation at each house created challenges for interpreting long-term field monitoring and performance testing data. Despite these challenges, the data offered interesting insights into duct system performance and served to validate the system performance calculations.

Building on the qualitative findings from the field demonstration, a combination of analytical calculations and modeled analysis was used to determine the potential energy savings and cost effectiveness of the retrofit strategy. Section 6 outlines the analytical methodology used to develop the effective and apparent R-values for each strategy of duct insulation. Due to added system complexity, a finite-element heat transfer analysis was required to calculate these values for the buried duct strategy. The finite-element heat transfer model showed that encapsulating the ductwork in 1.5 in. of ccSPF (R-6.7 h-ft^2-°F/Btu-in.) can improve the existing R-4.2 flexible ductwork to values between R-9 and R-13, depending on the size of the duct. Burying the encapsulated ductwork (to create buried and encapsulated ducts) will further increase the effective R-values to between R-16 and R-31.

Using the R-values calculated in Section 6, the effective and apparent heat transfer coefficients (UA values) for the duct systems of the three Jacksonville homes were calculated, and are presented in Section 7. This analysis was validated by comparing the results with test data for each home. The reduction in apparent UA values, based on field data, correlated well with the theoretical UA value reduction as the analysis in Section 6 shows. The values were found to be within 10% of each other, which is a reasonable error given that the calculation assumes steady-state operation.

The heat transfer coefficients developed in Sections 6 and 7 were then used to determine the efficiency of the thermal distribution systems, based on the ASHRAE Standard 152-2004 methodology (ASHRAE 2004). This is covered in Section 8. Both delivery effectiveness and distribution system efficiency were calculated. The calculations showed that duct leakage has a significant impact on delivery effectiveness, as a result of the direct relationship between duct leakage and duct losses.

Duct leakage rates were substantially reduced through encapsulation with ccSPF. For the houses with an air-handling unit in the living space, duct leakage to the outdoors was reduced to rates typical for houses with ducts in the living space. For the house with an air-handling unit in the garage, the duct leakage rates were dramatically reduced, but not to levels associated with ducts in the living space.

In Section 9, the condensation potential of buried and encapsulated ducts is explored further using modeling. For this analysis, the steady-state two-dimensional thermal model developed in Section 6 was combined with a one-dimensional, dynamic, hygrothermal model to predict the potential for condensation on the surface of the duct. This analysis was conducted for both buried and buried and encapsulated ducts using the worst case configurations. The results from the analysis predict condensation issues for the buried ducts without additional ccSPF insulation, which was observed by Griffiths et al. (2002). The analysis did not predict a condensation issue for the buried and encapsulated ducts as specified.

Finally, Section 10 presents information on the predicted energy savings associated with this retrofit and an assessment of cost effectiveness. Predicted energy savings were based on a calibrated Building Energy Optimization model. The modeled energy savings, which range from 5%–20% of total energy use for the three houses, appear reasonable in comparison to the predicted cooling and heating energy savings derived from the ASHRAE 152 delivery system efficiencies (ASHRAE 2004). These savings show that nearly all of the thermal losses and gains from the pre-retrofit duct systems were mitigated through these strategies. A cost-effectiveness analysis determined that the buried and encapsulated duct retrofit achieved $10 in annualized savings. The encapsulated-only strategy yields $141 in annualized savings. The higher annualized savings of the encapsulated-only strategy is due, in part, to avoiding the material and labor requirements associated with duct reconfiguration and blown-in insulation.

Based on this research study, encapsulated and buried and encapsulated ducts were found to dramatically improve the distribution efficiency of existing ductwork. Pre- and post-retrofit distribution system efficiencies were calculated using ASHRAE Standard 152-2004. The best case scenario estimates a post-retrofit distribution system efficiency of 97%–98%. Potential energy savings of 8%–20% per year were predicted through simulation. The predicted total energy savings are consistent with mitigating the majority of the duct losses from the homes. Energy savings associated with thermal losses and gains for these houses had a strong correlation with duct leakage to the outdoors, resulting in a significant range of potential energy savings. Encapsulated and buried and encapsulated ducts were found to be cost effective.

This research has been incorporated into the U.S. Department of Energy (DOE) Challenge Home National Program Requirements (DOE 2012). Although forced-air ducts are typically required to be inside the home's thermal and air barrier boundary, Section 10(c) of DOE (2012) allows an exception for buried and encapsulated ducts. Under this exception ductwork must be encapsulated with at least 1.5 in. of ccSPF and buried under 2 in. of blown-in insulation.

Acknowledgments

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1 Introduction

Heat gains and losses from ductwork installed in unconditioned spaces—such as attics, crawl spaces, and garages—can contribute significantly to the overall heating and cooling loads of single-family residential buildings. Unfortunately, installing ductwork in unconditioned spaces is a common construction practice throughout the United States. In the early 1990s, approximately 35% of American single-family homes contained ductwork installed in unconditioned spaces (Modera 1993). Over the past two decades, the number of homes with ductwork has increased considerably. Nearly all new single-family houses have ducted distribution systems; during the late 1990s, the percentage was estimated at 96% (National Association of Home Builders Research Center 1999). As a result, the percentage of housing units containing central forced-air cooling and/or heating systems has increased significantly, from 66% in 1993 (Energy Information Administration [EIA] 1993) to 76% in 2009 (EIA 2009).[2]

Although most studies emphasize the degree of duct losses in unconditioned spaces, estimates of these losses differ greatly, ranging from 10% to 45% (EPA 2009; Siegel et al. 2003; Vineyard et al. 2003; Jump et al. 1996; Palmiter and Francisco 1994; Modera 1993; Andrews and Modera 1992).[3] Duct leakage rates to the outside, which commonly vary from as little as 3% to more than 20%, are compounded by large temperature differentials between the conditioned air inside the duct and the air in the unconditioned space. During the cooling season, 55°F conditioned supply air can be separated from 120°F ambient attic air by duct insulation with a rated thermal resistance as low as R-4.2 (h-ft^2-°F/Btu). During the heating season, this temperature differential can be even higher, with 110°F conditioned air passing through an attic with a 20°F ambient temperature.

The wide range of duct loss estimates cited here demonstrates that duct losses can be reduced substantially for very leaky and underinsulated systems by properly sealing and insulating ductwork. (See Aldrich and Puttagunta 2011 for proper techniques.) Even when properly sealed and insulated, however, the duct losses of traditional duct systems commonly account for

[2] The authors calculated these percentages using the Public Use Microdata Files furnished by the EIA for the 1993 and 2009 Residential Energy Consumption Surveys.

[3] ASHRAE 152-2004 (See 2004; Section 8) defines duct losses in various ways, depending on the use of the duct loss term. Delivery effectiveness (DE) includes both thermal losses and duct leakage losses. Thermal losses represent the heat transfer through the duct material and any insulation. Duct leakage occurs when the conditioned air escapes through gaps and cracks in the ductwork. The physical location of the ductwork, duct insulation level, and duct sealing all affect the magnitude of the DE. Distribution system efficiency (DSE) includes DE, but also accounts for system cycling, fan power, thermal regain, equipment capacity, and air infiltration. Each term is calculated for heating and cooling design and seasonal conditions. Design conditions represent the efficiency under peak loads; seasonal conditions represent the losses over the entire heating or cooling season. The cited studies calculate duct losses in various ways and do not necessarily correspond to the definitions given in ASHRAE 152-2004. Because DE and DSE are typically similar under both design and seasonal conditions, the values given in these studies are directly compared to demonstrate the magnitude of the duct losses. In this report, the term duct loss is used generically for DE and DSE under design, seasonal, or other conditions. DSE and DE are used when they directly correspond to the conditions defined under ASHRAE 152-2004. Design and seasonal conditions are noted if applicable.

approximately 10% of the heating and cooling loads.[4] As a result, more aggressive strategies are needed to further reduce duct thermal losses. The primary methods, which are discussed in Sections 1.1 and 1.2, involve placing ducts within the thermal enclosure and burying ducts beneath loose-fill insulation. The encapsulated and buried and encapsulated duct strategies seek to achieve similar benefits. Although this report focuses on using these strategies as a retrofit methodology for existing homes, these methods can be employed with minimal changes in new construction.

1.1 Ducts in Conditioned Space: Current Practice

With proper planning and careful attention to detail, the thermal losses associated with ductwork can be eliminated in new construction by placing ducts within the thermal enclosure. In new construction applications, ductwork can be placed within the thermal enclosure using one of four methods: (1) expanding the thermal enclosure to incorporate the unconditioned space (e.g., insulating attics at the roof deck and insulating basements at the basement walls); (2) installing ductwork in a soffit or dropped ceiling; (3) installing ductwork between floors; and (4) using a modified truss to create a plenum for ductwork in the attic (Roberts and Winkler 2010; Hendrick 2003; Consortium for Advanced Residential Buildings [CARB] 2000).

New construction strategies for placing ducts in conditioned space cannot always be applied to existing homes. In retrofit applications, Methods 2 through 4 are typically impractical. Method 1, incorporating the unconditioned space into the thermal enclosure, is a more common retrofit strategy, but it can have significant disadvantages associated with lower energy savings, higher costs, and increased moisture. For ducts placed in attics, which is the principal subject of this report, Method 1 results in insulating the attic at the roof deck and incorporating an unvented attic into the design. Insulating the attic at the roof deck increases the thermal enclosure surface area, which results in larger space-conditioning loads from the enclosure (Hendrick 2003). Although this penalty can be overcome by savings from ductwork thermal losses, the net energy savings (duct savings minus increased enclosure loads) might be less than those achieved with other methods of placing ducts within the thermal enclosure.

Furthermore, building codes require minimum levels of air-impermeable insulations (International Code Council [ICC] 2009), and insulation must be installed so that it does not become dislodged from the roof deck assembly. As a result, closed-cell spray polyurethane foam (ccSPF) insulation is typically used to insulate buildings at the roof deck. Achieving the equivalent R-value at the roof deck using ccSPF is significantly more expensive than installing loose-fill insulation along the ceiling plane. The larger surface area of the roof deck results in higher costs compared to ceiling insulation, and ccSPF is comparatively more expensive than loose-fill insulation. Insulating the building at the roof deck using ccSPF, however, does yield greater air sealing benefits than typical ceiling insulation methods.

Additionally, the moisture dynamics of insulation at the roof deck must be carefully addressed to prevent serious moisture-related problems. Minimum values of air-impermeable insulation are required by Table R806.5 of the *International Residential Code for One- and Two-Family*

[4] This figure is an approximate number derived from the data presented in the literature (EPA 2009; Siegel et al. 2003; Vineyard et al. 2003; Jump et al. 1996; Palmiter and Francisco 1994; Modera 1993; Andrews and Modera 1992). These might apply to DE and DSE under both design and seasonal conditions generally as an approximate value.

Dwellings to prevent condensation on the inside surface of the insulation during the heating season (ICC 2009). Solar radiation can drive moisture from wetted asphalt shingles into the structural sheathing during the cooling season, causing shingle buckling and sheathing deterioration (Lstiburek 2006; Hendrick 2003).

1.2 Buried Ducts: Past Research and Current Practice

Given the many barriers associated with retrofitting the building to include existing ducts within the thermal enclosure and the resistance of some builders to carefully plan for ducts in conditioned space, other methods are needed to address ductwork thermal losses in new and existing homes. Burying ductwork beneath a layer of loose-fill insulation (Figure 3) has been proposed as a comparable alternative to ducts in conditioned space. This method has received significant attention under the Building America Program and has been shown to substantially reduce duct thermal losses (Griffiths and Zuluaga 2004; Griffiths et al. 2004; Vineyard et al. 2004; Griffiths et al. 2002).

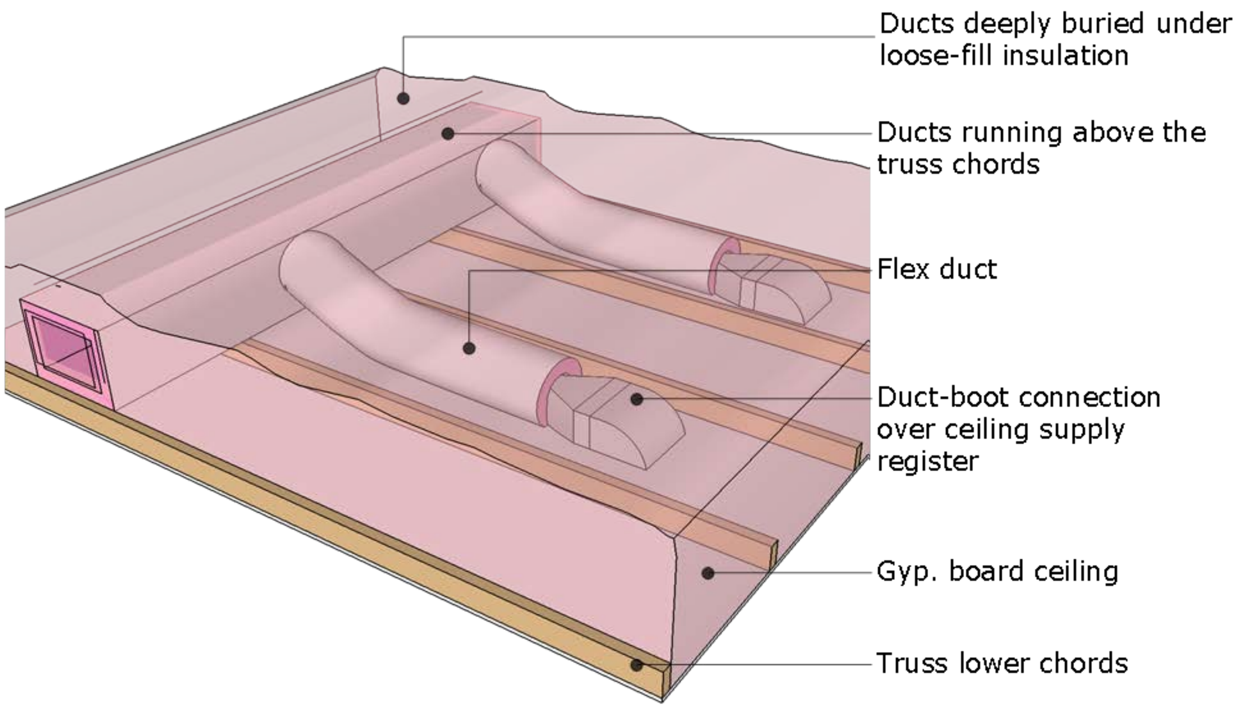


Figure 3. Detail of buried ducts

For new construction projects, the ductwork is installed as close to the ceiling plane as possible to maximize insulation coverage. The ducts are covered with insulation, which provides thermal resistance for the ductwork and boosts the R-value of the existing ceiling insulation. Although buried ducts do not eliminate duct losses entirely, the energy savings can be similar to those achieved by implementing Method 1 as discussed in Section 1.1, in which the attic is insulated at the roof deck. Some thermal losses will still be present with buried ducts, but these losses might be less than or equal to the increased thermal loads resulting from the increased enclosure area associated with Method 1.

The effective R-values of deeply buried ducts are between 25 and 31 (Griffiths et al. 2004). These values are greater than or equal to many attic insulation levels in existing homes. Although burying ducts deeply is uncommon and requires careful attention, the practice, when combined with proper duct sealing techniques, can reduce thermal losses substantially in comparison to traditional duct installations. Furthermore, in retrofit applications, the buried duct strategy can be implemented at a fraction of the cost associated with insulating the attic at the roof deck because the approach uses less expensive loose-fill insulation to cover the existing ductwork.

Buried ducts, however, are not well suited for hot-humid climates. After demonstrating buried duct benefits in hot-dry climates, Building America research was conducted to evaluate the strategy in hot-humid climates. After burial, duct jacket surface temperatures were observed to be lower than the dew point of the attic air; this creates a potential for condensation on the surface of the duct (Griffiths and Zuluaga 2004; Griffiths et al. 2004; Griffiths et al. 2002). As a result, a modified methodology to reduce the condensation potential was sought. Ductwork at a test home in Atlanta was encapsulated in a 1-in. layer of ccSPF insulation before being buried beneath loose-fill insulation. The buried and encapsulated duct strategy (Figure 4) implemented at this home successfully eliminated the condensation potential of buried ducts in a hot-humid climate (CARB 2003).

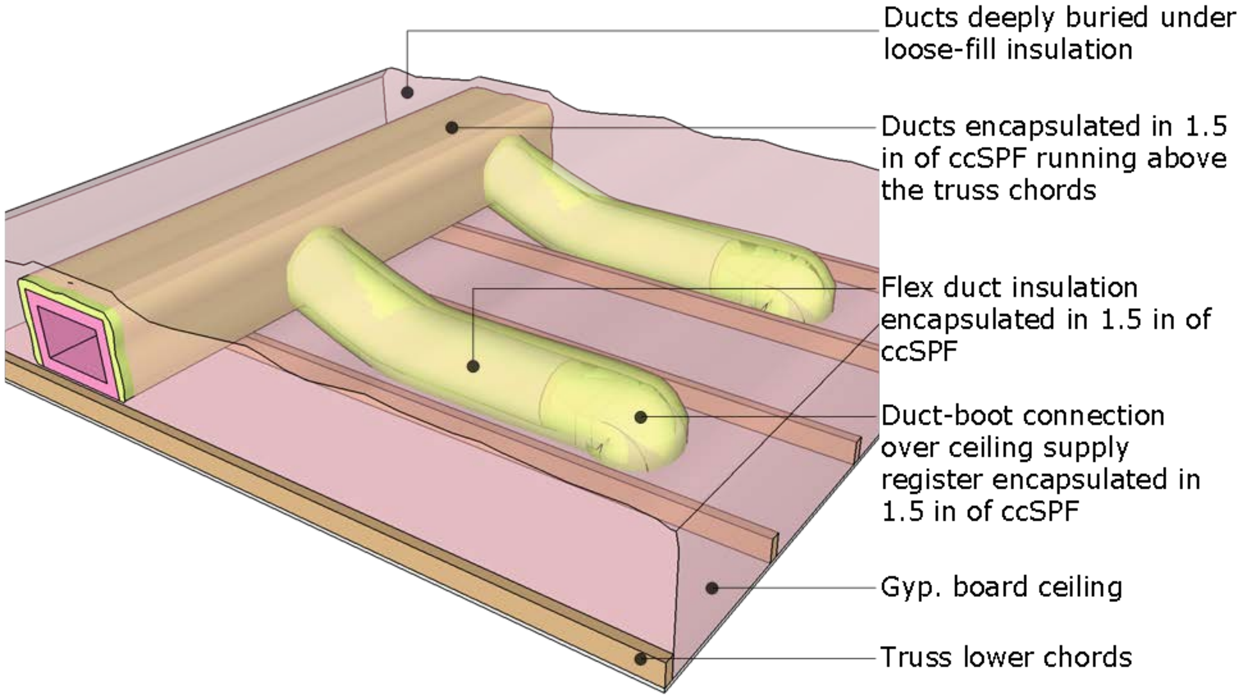


Figure 4. Detail of buried and encapsulated duct

The application of ccSPF, which has high R-values per inch and low vapor and air permeability, increases the thermal resistance of the duct insulation and reduces duct leakage by filling gaps and voids in the ductwork. Building on the buried duct concept, buried and encapsulated ducts start by encapsulating the ductwork before burying it beneath a layer of loose-fill mineral fiber insulation. In addition to the lower duct leakage rates expected from using ccSPF, installing additional insulation through the ccSPF and burying the ductwork beneath loose-fill insulation are expected to result in significantly higher R-values. Furthermore, the risk of condensation associated with buried ducts is expected to be eliminated by elevating the surface temperature of the outside vapor-impermeable layer of the duct above the dew point of the surrounding air.

1.3 Reducing Duct Losses in Existing Homes in Hot-Humid Climates

Recognizing that cost-effective and safe methods are needed to address thermal losses from ductwork in the current housing stock in hot-humid climates, it was clear that the feasibility of applying the buried and encapsulated duct strategy to existing homes warranted further research. Furthermore, more research was needed to validate the findings by CARB (2003) in hot-humid climates and quantify the energy savings potential of this strategy. The vast majority of single-family homes in the hot-humid climates in the United States have central forced-air cooling systems (see Table 1). Since conventional HVAC design manuals dictate that space-conditioning air in cooling-dominated climates be discharged from ceiling or high wall registers (Air Conditioning Contractors of America [ACCA] 1992) and living space is at a premium, the vast majority of these homes have ductwork installed in attics.

Table 1. Percentage of Households With Central, Ducted, Forced-Air Space-Conditioning Systems by Climate

Climate	Cooling (%)	Heating (%)	Heating and/or Cooling (%)
Very Cold/Cold	48.9	68.0	72.7
Hot-Dry/Mixed-Dry	60.6	67.1	73.0
Hot-Humid	82.5	79.4	86.1
Mixed-Humid	71.4	73.4	79.4
Marine	17.8	57.4	58.1
All Climates	61.3	70.9	76.3

Source: EIA (2009).

This report investigates the potential of two ductwork retrofit strategies employing ccSPF, buried and encapsulated ducts and encapsulated ducts alone. The encapsulated duct approach is a variation of the buried and encapsulated duct strategy that arose during the field retrofit because of feasibility limitations. Encapsulated ducts simply enhance the existing insulated ductwork by applying a layer of ccSPF. Requiring less modification and fewer contractors and materials, encapsulated ducts are expected to have higher R-values and lower duct leakage rates than existing ductwork. This study sought to explore the trade-offs in energy savings, installation cost, and installation ease between the two approaches.

When properly installed, these two duct insulation strategies are both compliant with the 2009 *International Residential Code for One- and Two-Family Dwellings* (ICC 2009). In general, the code allows spray-foam insulation to be applied to the exterior of ductwork (Section M1601.3) as long as the spray foam has a flame spread index no greater than 50 and a smoke developed index no greater than 450, is protected by an ignition barrier (Sections R316.5.3 and R316.5.4), and meets the general requirements for use in residential buildings (Section R316). As a result, buried and encapsulated ducts covered with at least 1.5 in. of mineral fiber insulation and installed in attics "entered only for purposes or repairs or maintenance" (meaning no storage or habitation allowed) meet these requirements (ICC 2009). Thermal barriers are not required for this type of attic, and 1.5 in. of fiberglass, which is considered mineral fiber insulation (ASTM 2011), meets the minimum requirements for ignition barriers.

Encapsulated ducts or buried and encapsulated ducts covered with less than 1.5 in. of fiberglass insulation can also be code compliant if the specific spray foam meets the broader requirements of Section M1601.3. Although not all ccSPF materials meet these requirements, the installed material has undergone testing to verify performance. Exposed applications of the spray foam used in this study are compliant with Section M1601.3, as described in the International Code Council Evaluation Service Report (International Code Council Evaluation Service 2012), and are therefore code compliant (International Code Council Evaluation Service 2010).

The primary goals of this study are to quantify the energy savings associated with encapsulated and buried and encapsulated ducts, along with their cost effectiveness and condensation potential. Although the field demonstration supplied valuable information about the installed performance of the distribution systems and important insights into the feasibility of this retrofit strategy, variations in field conditions necessitated supplemental data analysis. As with any field testing of occupied homes, quantifying energy savings is difficult because of the dramatic changes in occupant behavior and building system operation. Despite these difficulties, field evaluations are necessary to support other analytical methods with real-life data. In this report, computer modeling and analysis were used to calculate energy savings and condensation potential. Data from the field evaluation were used to validate these conclusions and determine cost effectiveness.

2 Previous Research

Previous research on buried ducts has focused on determining effective duct R-values, investigating the potential for condensation, and estimating associated energy savings in new construction applications. Unlike traditional hung ducts, the thermal resistance of buried ducts cannot be calculated by knowing the geometry of the duct insulation and its conductivity. To make an appropriate comparison with traditionally insulated duct R-values, effective R-values of buried ducts must be determined.

Using Algor FEA (Zoeller 2009), a two-dimensional, steady-state, finite-element heat transfer model, Griffiths and Zuluaga (2004) calculated effective R-values of ducts buried under various levels of loose-fill insulation. Effective R-values were defined as "the equivalent R-value that conventional hung ducts must be wrapped with to achieve the same thermal performance as buried ducts" (Griffiths and Zuluaga 2004; 723). Under this definition, effective R-values exclude the heat transfer between the conditioned space and the duct that results from burial in loose-fill insulation.

The primary driver of effective R-values was found to be the distance from the top of the insulation to the top of the duct, and the overall R-value of the attic insulation was found to be less important than the height of the insulation. Furthermore, the impact of insulation below the duct was minimal; effective R-values were unaffected by placing the ducts on the gypsum board ceiling surface, over loose-fill insulation, or over the lower truss cord. As a result, Griffiths and Zuluaga (2004) categorized buried duct insulation levels by the distance from the top of the insulation to the top of the duct. Ducts were defined as partially buried, fully buried, and deeply buried (see Figure 5).

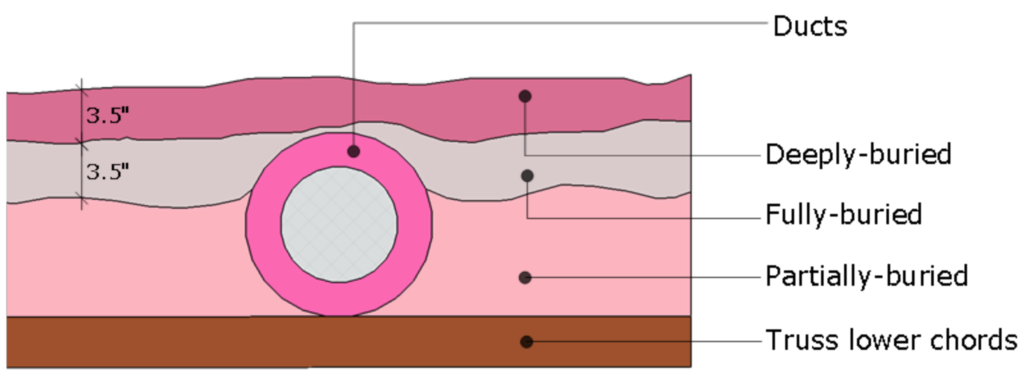


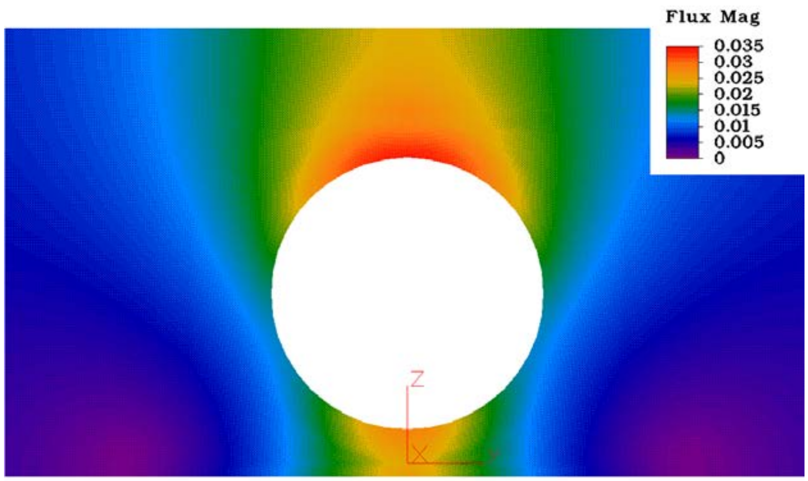
Figure 5. Categorization of duct insulation levels by burial class

For these levels of burial, effective R-values were calculated for fiberglass and cellulose attic insulation (Table 2). Although the effective R-values of ducts were found to be a function of the duct inner diameter, the listed R-values are an average of small and large duct simulations. These R-values became the basis of Table R3-38 of the *Residential Compliance Manual* (California Energy Commission [CEC] 2007; 2008).

Table 2. Effective R-values of Buried Ducts by Insulation Level and Type (h-ft^2-°F/Btu)

Loose-Fill Insulation Type	Deeply Buried	Fully Buried	Partially Buried
Fiberglass	R-25	R-13	R-9
Cellulose	R-31	R-15	R-9

Validating these theoretical effective R-values is difficult because the effective R-value explicitly excludes the nondetrimental heat transfer between the duct and the conditioned space (see Figure 6 for an image showing heat transfer). Validation has been attempted under laboratory conditions and in field testing (Griffiths et al. 2004; Vineyard et al. 2004), but the methods used in these validation studies do not exclude heat transfer between the duct and the conditioned space, resulting in a different definition of R-value. To address the conflation of these two R-value definitions in previous studies, this report distinguishes between effective R-values, which exclude heat transfer between the duct and conditioned space, and apparent R-values, which include heat transfer between the duct and conditioned space.



Source: CARB (2003)

Figure 6. Heat transfer between duct interior, conditioned space, and attic

Although apparent R-values are expected to be lower than effective R-values because they include all heat transfer across the surface of the duct, laboratory and field testing has not consistently supported this hypothesis. Griffiths et al. (2004) compared the performance of buried ducts against that of conventional hung ducts in two identical houses in Elk Grove, California. Apparent R-values determined through field testing were slightly higher than the effective R-values predicted by thermal modeling. Vineyard et al. (2004) used laboratory testing to calculate R-values and found apparent R-values slightly lower than the effective R-values found by Griffiths and Zuluaga (2004). The discrepancy between these results might be explained by the averaging used to calculate the effective R-values of buried ducts. For small or large ducts, the effective R-values could differ considerably from those shown in Table 2.

Research in Phoenix, Arizona, and Sacramento, California, successfully demonstrated that buried ducts do not have condensation issues in hot-dry climates. A demonstration in Melbourne, Florida, however, found a potential for condensation in a hot-humid climate. Even though the conditions supporting condensation were relatively short-lived and no damage was found, the condensation potential was possibly mitigated by leakage from the building enclosure and ductwork. In less leaky conditions, condensation could have been a greater problem (Griffiths et al. 2004; Griffiths et al. 2002). Chasar and Withers (2012) also observed condensation on the surface of buried ducts at a home in Cocoa, Florida. Laboratory testing determined that ducts cannot safely be fully buried in insulation when design dew point temperatures approach 80°F (Vineyard et al. 2004).

In a side-by-side evaluation of traditional ductwork and buried ducts, Griffiths et al. (2004) saw a measured improvement in distribution efficiency from 86% to 90%.[5] Under laboratory testing, Vineyard et al. (2004) reported seasonal distribution efficiency improvements ranging from 4% to 14% and design distribution efficiency improvements ranging from 5% to 31%. Seasonal distribution efficiency reductions represent annual energy savings; design distribution efficiency reductions represent potential space-conditioning system capacity reductions.

Field monitoring of buried and encapsulated ducts covered with 1 in. of ccSPF insulation saw no condensation potential during the monitored summer for a newly constructed home in Atlanta, Georgia. Observed ccSPF surface temperatures were safely above the attic dew point temperature. Although this study demonstrated the feasibility of buried and encapsulated ducts in new construction, no energy savings or distribution efficiency calculations to quantify the associated energy savings were reported (CARB 2003).

Most of the studies mentioned here have used temperature and relative humidity sensors to measure condensation potential. Using these sensors, the ambient air dew point is compared to the surface temperature of the ductwork. If the surface temperature is below the dew point of the surrounding air, there is a potential for condensation. Chasar and Withers (2012) used resistive moisture measuring strips in addition to temperature and relative humidity sensors. Both methods resulted in similar measures of condensation potential, validating both methods of measuring condensation potential.

[5] These values were measured over a period of time, and therefore do not correspond to either design or seasonal values.

3 Materials and Methods

In this study, three houses of similar size and vintage in Jacksonville, Florida, were monitored before and after duct retrofits during the summers of 2010 and 2011. These three test houses are single-story buildings that were constructed between 1980 and 1991 and built using typical Florida construction methods. Ductwork is constructed out of duct board or insulated flex duct and placed in vented attics with insulation at the ceiling plane. Air-handling units (AHUs) are located inside the house or in the garage.

System evaluations were performed through single-point performance testing at various project stages, long-term pre- and post-retrofit field monitoring, and house and system documentation. One house was retrofitted with encapsulated ducts, and the other two were retrofitted with buried and encapsulated ducts. This section summarizes the methodology used to monitor the pre- and post-retrofit performance of the duct systems in these three houses (Section 3.1) and the retrofitting methodology used to insulate the existing duct systems (Section 3.2). The performance testing and field monitoring methodologies were developed to gather as much information as possible about the temperature, relative humidity, and operation of the systems before and after duct insulation. Since encapsulated and buried and encapsulated ducts are a novel insulation strategy for ductwork in existing buildings, a retrofit methodology was developed to achieve the desired attributes of practical applications, to maximize energy savings, and to minimize condensation potential.

3.1 Monitoring Methodology

The performance of pre- and post-retrofit ductwork assemblies was measured using performance testing and long-term monitoring. To assess the long-term performance both before and after implementing the encapsulated duct and buried and encapsulated duct strategies, data loggers were placed at multiple distribution system locations. Measurements were taken at 1- or 2-min intervals. Operation of the space-conditioning equipment was measured at the AHU and condensing unit using state sensors, which have a Boolean output of either “on” or “off.” Measurements were taken using the equipment listed in Table 3.

During the pre- and post-retrofit assessments, the following measurements were taken through performance testing:

- Pressure drop across the AHU and coil (Pa)
- Temperature change across the AHU and coil (°F)
- Total AHU supply and return airflows (cfm)
- Room airflows (cfm)
- Duct leakage—total and leakage to the outside, supply and return (cfm @ 25 Pa)
- Infiltration of building enclosure (ACH_{50})
- Power consumption of the AHU and condensing unit (W).

Table 3. Equipment Used for Performance Testing and Long-Term Monitoring

Measurement	Equipment Needed
Pressure Drop Across the AHU and Coil	DG-700 Digital Pressure and Flow Gauge
Temperature Change Across the AHU and Coil	HOBO U12-006 data logger with TMC6-HD Probe
Total AHU Supply and Return Airflows	True Flow Air Handler Flow Meter
Room Airflows	Alnor Low Flow Balometer
Duct Leakage—Total and Leakage to the Outside, Supply and Return	Minneapolis Duct Blaster System with DG-700 Digital Gauge
Infiltration of Building Enclosure	Minneapolis Blower Door System with DG-700 Digital Gauge
Infrared Thermal Imaging	Flir B50 Infrared Camera
Temperature of Airstream	HOBO U12-006 data logger with TMC6-HD Probe
Surface Temperature	HOBO U12-006 data logger with TMC6-HE Probe
Indoor/Attic Air Temperature and Relative Humidity	HOBO U12-011 data logger
Outdoor Air Temperature and Relative Humidity	HOBO U23-002 data logger
Relative Humidity of Airstream or Surface	HOBO U23-002 data logger
AHU and Condenser Run Times	HOBO U9-001 data logger with CSV-A8 Probe

At each of the three homes, temperature (°F) was measured at the following locations:

- Discharge airstream of longest run
- Discharge airstream of three typical runs
- AHU supply
- AHU return
- Surface of duct jacket at three typical runs
- Surface of ccSPF insulation at three typical runs (post-retrofit only)
- Surface of boots at three typical runs (pre-retrofit only for all houses and one boot per house post-retrofit)
- Attic ambient air
- Living space ambient air at two locations
- Outdoor ambient air.

Relative humidity (%) was measured at the following locations:

- Discharge airstream of longest run
- Discharge airstream of three typical runs
- AHU supply
- AHU return
- Surface of ccSPF insulation at three typical runs (post-retrofit only)
- Surface of boots at three typical runs (pre-retrofit only)
- Attic ambient air
- Living space ambient air at two locations
- Outdoor ambient air.

3.2 Retrofitting Methodologies

The methodologies for implementing the two ductwork retrofit strategies were influenced by concerns about maintaining quality installation, minimizing condensation, and streamlining the installation, along with practical concerns identified by the entire team. The team included the contractor responsible for applying the ccSPF insulation, the ccSPF manufacturer, the HVAC contractor, and the Building America researchers. The researchers were primarily concerned with ensuring that ductwork was placed as close as possible to the ceiling plane, the ccSPF application was consistent and of sufficient thickness to mitigate the possibility of condensation, and the installation was code compliant. The insulation contractor was primarily concerned with preventing leakage of ccSPF through the boots of the ductwork into the home and preventing blowback of fiberglass insulation during ccSPF application, which can affect visibility and insulation adherence to the ductwork.

Attic accessibility, temperature, and location of existing services (e.g., plumbing, television cable, security wires, and fireplace flues) also needed to be taken into account. Based on previous experience in Atlanta, a ccSPF thickness of 1.5 in. was selected to ensure that the ductwork would be covered in enough insulation to prevent condensation. This insulation level is slightly higher than that used in Atlanta because of the differences in climate.

Sections 3.2.1 and 3.2.2, respectively, describe the general strategy for encapsulated and buried and encapsulated duct retrofits. Although these methods serve as a general guideline for retrofitting existing ducts, differences between ductwork systems merit slightly different treatment, particularly when reconfiguring the existing system layout. The differences between the methods used at the three tested houses are discussed in Sections 3.2.3 through 3.2.5.

3.2.1 Buried and Encapsulated Ducts

For buried and encapsulated ducts, a four-phase methodology was employed. The insulation contractor removed the existing ceiling insulation, the HVAC contractor reconfigured the ducts, a trained installer applied the ccSPF, and the insulation contractor then installed the loose-fill insulation. This approach requires coordination between an insulation contractor and an HVAC contractor.

Additional coordination and home access was required for laborers to remove insulation and seal the register boots. The ccSPF contractor opted to remove all blown-in insulation and batt insulation as a precaution to eliminate any problems during ccSPF application. The following list explains and illustrates the steps taken during the buried and encapsulated ducts retrofit.

1. Remove existing insulation from around the ductwork by removing batt insulation and/or vacuuming out loose-fill insulation. Note: To minimize the number of site visits, laborers might be able to complete this step while the ccSPF equipment is being set up.

2. Seal around the boots with polyurethane-based insulating foam to prevent leakage into living space during encapsulation. Note: The blades of the interior diffusers were typically closed during ccSPF application for added protection.

3. Cut down or remove supports holding ductwork and plenum boxes above the truss bottom cords or gypsum board.[6] Varying degrees of reconfiguration could be appropriate, depending on the configuration of the ductwork and attic.[7] This work, including extending sections of ductwork, was done by an HVAC technician.

4. For ductwork that passes over soffits or other areas that have a large gap between the duct and the sheetrock, 1.5-in. rigid insulation board can be placed underneath the ductwork to ensure that the ductwork is entirely encapsulated in an air- and vapor-impermeable layer of insulation. It is preferable to seal the ductwork directly to the sheetrock but limited access for the ccSPF gun and gear must be considered.

[6] Ducts should be supported in compliance with local building codes and manufacturer specifications.

[7] Major reconfigurations might require duct sizing calculations using ACCA Manual D (ACCA 2009). For this project, duct reconfigurations were minor, and no efforts were made to rigorously size duct reconfigurations using Manual D.

5. Protect existing services, such as flues and pipes, from ccSPF using duct board or rigid insulation. The appropriate material will depend on the application.

6. Encapsulate ductwork in at least 1.5 in. of ccSPF. The minimum thickness must be maintained consistently on all sides to mitigate condensation concerns.

7. Bury encapsulated ductwork in loose-fill insulation. The insulation must cover the ductwork to be considered fully buried. Code requires a minimum of 1.5 in. of coverage over the ducts for ccSPF materials that do not meet the flame spread requirements. Coverage of 3.5 in. over the duct surface achieves a deeply buried rating.

3.2.2 Encapsulated Ducts

For one of the houses in this study, good duct burial could not be achieved even if significant duct reconfiguration had been undertaken. In addition, the project team was concerned that relocating the ductwork would significantly affect the room airflows. As a result, the team opted to evaluate the benefits of the encapsulated duct strategy.

For encapsulated ducts, the methodology is similar. This strategy, however, is simpler and requires no duct reconfiguration or loose-fill insulation. This is a single-contractor approach, requiring only ccSPF application. Selecting the appropriate method for each house will depend on cost, feasibility, ccSPF material code compliance, and energy performance goals. The following list describes and illustrates the encapsulated duct strategy.

1. Remove existing insulation from around the supply and return register boots by moving batt insulation or vacuuming out loose-fill insulation.

2. Seal ductwork with polyurethane-based insulating foam to prevent leakage into living space during encapsulation.

3. For ductwork that is not hung above the ceiling or does not have sufficient clearance below for proper ccSPF application, place 1.5-in.-thick rigid insulation board underneath the ductwork to ensure that the ductwork is entirely encapsulated in an air- and vapor-impermeable layer of insulation.

4. Encapsulate ductwork in at least 1.5 in. of ccSPF using a material that has the necessary ratings to demonstrate code compliance. Leave the ductwork exposed.

3.2.3 House 1 Retrofit

The existing ductwork in House 1 consisted of R-4.2 flexible ductwork configured with a primary trunk extending the length of the house and branch take-offs serving the spaces. The AHU is located inside the conditioned area and has a louvered door on the return, eliminating the need for return ductwork. Branches are connected to the primary supply trunk using plenum boxes constructed with R-4 fiberglass duct board, which are placed on plywood platforms. Duct runs are hung from the rafters with strapping and connected to sheet metal boots at the ceiling plane (Figure 7). This was the only home served by an AHU with a variable-speed fan motor.

Ductwork at House 1 was retrofitted with a buried and encapsulated duct strategy. Of the three, this house underwent the most significant duct reconfiguration. During the duct retrofit, the plywood platforms supporting the plenum boxes were removed to lower the main trunk closer to the ceiling plane. The straps supporting the ducts were removed, lowering them to the ceiling plane. Where possible, ductwork was reconfigured to minimize elbows and eliminate duct overlap. The reconfiguration resulted in approximately 21 linear feet of additional ductwork routed closer to the gypsum board. These modifications maximized duct burial to the greatest extent possible, but still primarily used the existing duct system.

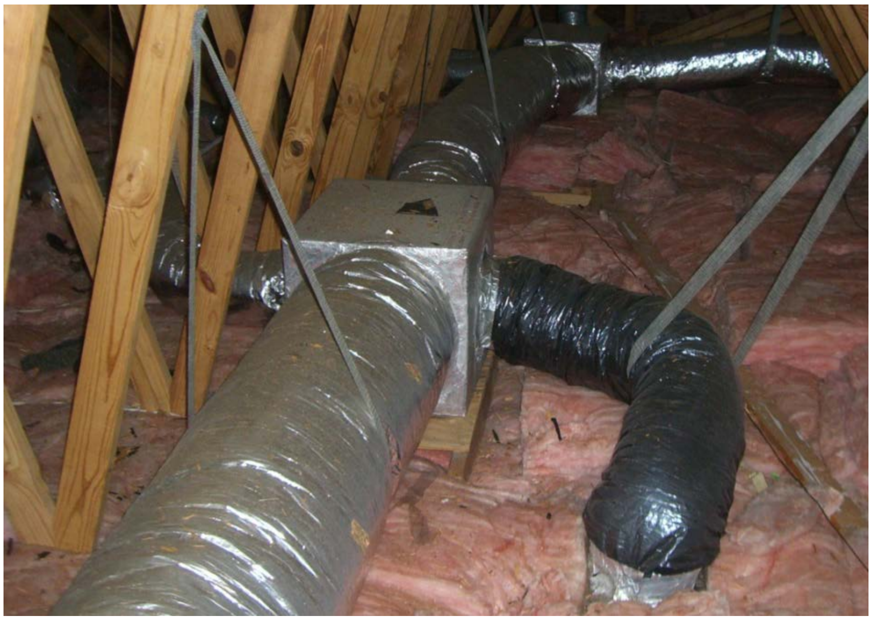


Figure 7. Existing ductwork at House 1

3.2.4 House 2 Retrofit

Existing ductwork in House 2 consisted of a main rectangular supply trunk and rectangular branch supply take-offs. The AHU is located in the garage, near a wall adjacent to the conditioned space. All supply ductwork runs through the garage and into the attic. There are two returns, a central return entering the AHU return plenum through the partition wall, and a second return serving the far side of the house via a flex duct routed through the entire attic and garage. The supply ductwork consists of R-4 duct board rectangular ducts (Figure 8), and the return ductwork consists of a large R-4.2 flex duct (Figure 9).

House 2 was retrofitted with a buried and encapsulated duct strategy. During the retrofit, the majority of the supply ductwork was left in place because it was already resting on the lower truss cords. One exception was a supply duct that had been built to cross over the return duct (Figure 10). The duct board return had since been abandoned. The supply duct was replaced with a small flex duct using a side take-off, enabling this ductwork to drop low against the ceiling plane. In conjunction with this modification, the abandoned duct board return was removed and the majority of the return ductwork was relocated to the center of the attic and lowered to the truss cords (Figure 11). The abandoned return ductwork was removed and discarded.

Figure 8. Supply ductwork for House 2

Figure 9. Return ductwork for House 2

Figure 10. Supply ductwork jump over abandoned return ductwork

During removal of the ceiling insulation before encapsulation, a large opening in the far end of the supply trunk was discovered. This take-off protruded from the bottom of the trunk toward the ceiling, and was most likely meant to serve a register that was never installed. The supply air had been escaping to the attic since the system was installed. This opening was sealed before encapsulation. This problem was not discovered before pre-retrofit monitoring began. As shown in Figure 12, the ceiling in this home had a number of dropped areas for ceiling coffers. In these locations, the batt and the blown insulation were very deep. The insulation contractor removed much of this insulation and used rigid insulation as a substrate for the ccSPF application. Much of the batt insulation could have been left in place, but the open duct would not have been detected.

Figure 11. Duct reconfiguration at House 2

Figure 12. Open duct take-off at House 2

3.2.5 House 3 Retrofit

House 3 was similar to House 1 in ductwork specifications. Existing R-4.2 flexible ductwork was configured with a large main trunk running the length of the house and flex duct branch take-offs. The AHU is located inside the conditioned area and served by a louvered door on the return, eliminating the need for any return ductwork. Branches were connected to the supply trunk using plenum boxes constructed with R-4 fiberglass duct board, which were placed on plywood platforms. Duct runs were hung from the rafters and connected to sheet metal boots at the ceiling plane.

In this home, the main living room has a cathedral ceiling and the large duct trunk is suspended from the center of trusses for a long run (Figure 13). Even if this trunk were lowered, it would be resting on the angled cathedral ceiling plane. Under those conditions, burying the large duct would have been difficult and might have necessitated baffling at the perimeter to prevent insulation from blocking the limited attic vents. In addition, many of the branch ducts were resting on high raised platforms.

Lowering the ductwork would have resulted in severe duct bends, making burial challenging. The potential impact of the duct reconfiguration on room airflows was difficult to predict, but the project team opted to forgo duct reconfiguration in this house. As an alternative to burying the ductwork, the team considered wrapping the ducts with fiberglass duct wrap insulation or draping them with fiberglass batts. Either approach would have provided the minimum 1.5-in. coverage over the ccSPF and resulted in a minimal additional amount of insulating value. Ultimately, the manufacturer confirmed that the ccSPF could be left exposed, so no additional insulation was installed.

No reconfiguration was necessary at House 3 because it was retrofitted using the encapsulated duct strategy (see Figure 13 for finished retrofit). The ccSPF contractor was initially concerned that the raised ductwork would be difficult to insulate because of the high application pressures, but the installer was able to get access to all sides of the ductwork.

Figure 13. Finished encapsulated duct hung from roof deck

4 Retrofit Methodology Evaluation

Retrofitting these houses resulted in valuable information about the coordination issues, practicality, and difficulties associated with burial and/or encapsulation of the existing ductwork at the three test homes. Section 4.1 describes the lessons learned. Section 4.2 outlines some quality control issues experienced during the retrofit process.

4.1 Lessons Learned

During the retrofit process, many important details about the encapsulated and buried and encapsulated duct retrofit methodologies were uncovered. Even though the research team attempted to preemptively solve any problems that might arise, unforeseen issues were inevitably discovered during the installation. Furthermore, some of the actions taken to remove obstacles during the retrofits were potentially unnecessary. The following bullet points list potential areas of improved installation efficiency, as well as the issues that arose during the installation and potential solutions. As with any new building methodology, processes will become more streamlined as more installations take place.

- Baffling materials might be required to enable mounding of loose-fill insulation to achieve proper burial of vertical duct trunks and raised or larger diameter duct runs (Figure 14).
- Baffling might be necessary to partition off flues, chimneys, or other house components that should not be in contact with the ccSPF or loose-fill insulation. Foil-faced duct board was typically used because it is rated for use in attics, comes in narrow pieces that can be easily transferred to the attic, can be cut with a knife, and can be secured with metal tape (Figure 15).
- Venting for existing ventilation fans cannot be blocked by the added blown-in insulation. In one home, the fan was unducted and vented to the attic. Existing unducted ventilation fans should be ducted to an exterior termination.
- Attic venting at the ridge, gables, and perimeter should be assessed to ensure that added blown-in material will not block the airflow.
- Electrical, telephone, cable, security, and other wiring could be permanently spray foamed into place (Figure 16).
- Plumbing routed through the attic, such as the roof-mounted solar pool heating system installed in one test home, could be covered with foam.
- Access for installers can be difficult because of the cables, plumbing, and other equipment located in the attic.
- Can lighting, exhaust fans, and other electrical equipment located in the ceiling plane can get covered in foam and/or require baffling for protection during the retrofit.
- During the summer, high attic temperatures can be a safety concern for the ccSPF installers. The ccSPF material used in these installations is heated before spraying, further

increasing the attic temperature. In addition, installers must wear protective masks and suits. Forced ventilation air was used in the attics during these applications, although it was not cooled.

- Attic access for ccSPF installation must be considered. During screening of potential installation sites, houses with adequate access for hoses and equipment were selected. These houses all had attic access stairs located in the garage, eliminating the need to enter the house with hoses and ccSPF equipment.

- During the ccSPF installation, the HVAC system should be disabled. For all three houses, the AHUs were turned off during the application. The ccSPF contractor raised concerns about any odors escaping into the living space.

- Coordinating with occupants is important. If the AHU system will be disabled for a few hours, any pets or occupants should leave the house to avoid fumes and maintain comfort. Every attempt was made to minimize the number of times access to the house was required. To install sensors for this research project and conduct the performance testing, access to these houses was required more frequently than would be needed in a typical application.

- The need for boot sealing should be further evaluated. It might not be necessary, but in these homes it was left to the discretion of the contractor. If future investigations find that this is not required, it could result in lower costs.

- The need for insulation removal should be further evaluated. Fully removing the insulation might be unnecessary. Cutting it and rolling it back before applying the ccSPF might be sufficient. On the other hand, removing existing attic insulation offers an excellent opportunity for sealing the ceiling planes, which would result in even greater energy and comfort improvements.

- Sequencing of this retrofit application requires coordination to minimize costs and expedite the installation. Ideally, the ccSPF can be applied in a few hours in the morning and a second installer can follow behind with a truck to install the blown-in loose-fill insulation. For these houses, the same contractor performed both services, but with two separate crews. Additional time must be left for any insulation removal, boot sealing, and/or duct reconfiguration.

- Duct reconfiguration should be undertaken with care and evaluated for each home. For these retrofits, minimal duct changes were made and the pre- and post-retrofit airflows were verified by testing. Although airflow verifications might not be necessary for retrofits with minimal reconfigurations, the airflows could be affected if significant changes are made to ductwork. In this case, it might be necessary to install flow dampers and verify airflows after the retrofit is complete.

- Using an HVAC contractor for the duct reconfiguration is recommended. Typically, insulation contractors are not familiar with the impact of duct changes on the system airflows. Although the insulation contractor can do minimal duct reconfiguration (cutting down strapping, etc.), changes to the distribution system can void any contractor warranties associated with the installed duct system. Local codes can also require a licensed HVAC contractor to perform all work related to the HVAC system.

- The buried and encapsulated duct strategy is a multitrade effort. For these homes, Building American Program researchers coordinated with the contractors and homeowners. It is unlikely that a homeowner would be willing to serve as the point of coordination to implement this strategy. To offer this strategy as a package, two or three contractors would be required: a ccSPF installer, a blown-in insulation installer, and an HVAC installer (could be optional, if code allows). Ideally, a company that offers a full range of home retrofit services could furnish this package. As an alternative, organizations could partner to offer the package, with one contractor serving as a coordinator.

- The encapsulated duct strategy is a single-trade effort. It requires significantly less coordination, fewer periods of access to the home, only a single insulation material, and lower costs. Insulation contractors might need to be trained to recognize major distribution flaws that must be corrected by an HVAC contractor, such as the one discovered at House 2. An HVAC contractor might be required to consult on a case-by-case basis if concerns arise and the homeowner opts to pursue them.

- Careful attention must be paid to quality control of the ccSPF installation. This is discussed further in Section 4.2.

Figure 14. Baffling used to ensure proper burial of supply duct plenum (post-encapsulation and pre-burial)

Figure 15. Baffling used to prevent ccSPF application on flue duct

Figure 16. Electrical, telephone, and other wiring permanently spray foamed to the ceiling and ductwork during retrofit

4.2 Quality Control

The most important observation from the field demonstration was the inadequate application of ccSPF at several specific locations of the ductwork and the general difficulty with maintaining consistent insulation thickness. This observation is not intended as a critique of the installation contractors. The installers were challenged by extremely high attic temperatures, limited access for spraying, a tight project schedule, varying site conditions, the unique addition of devices and wiring for system performance monitoring, and minimal available information on the preferred installation details. Overall, all three installations were very successful, but it is important to document opportunities for future improvement.

At House 1, the top of the supply plenum box that extends vertically into the attic was not foamed (Figure 17). Even with baffling, this large vertical riser was difficult to bury beneath a deep fiberglass insulation. Although the lack of insulation reduces the R-value of this duct section and the overall distribution system efficiency, it is unlikely to create a condensation problem. Since this problem was not discovered until after the spray foaming was finished, the top of the plenum box was covered with R-4 rigid board and sealed with metal tape (see Figure 14). The supply plenum requires particularly close attention. Because it is closest to the AHU, the supply plenum has the highest system pressure and distributes the most extreme air temperatures.

Figure 17. Improperly spray-foamed plenum box at House 1

Furthermore, at several locations at House 1 where the ductwork runs perpendicular across the lower truss cords and other locations where the ductwork was slightly elevated, the underside of the ductwork was not completely covered in spray foam. The inadequate application of spray foam at the underside of the ductwork could create the potential for condensation because the duct jacket, which might be below the dew point of the surrounding air, was exposed.

Although somewhat difficult to see, Figure 18 and Figure 19 show the undersides of ductwork that were left exposed after the ccSPF was applied. Getting the spray nozzle low enough to apply foam in these locations was challenging. Two options could be used to solve this problem. The installer can cocoon the duct in ccSPF and directly seal it to the sheetrock (Figure 20). Alternatively, a piece of rigid insulation can be inserted under the ductwork to act as a substrate for the foam and ensure that a minimal insulation thickness is achieved on the underside of the ducts (Figure 21).

In addition, the insulation thickness varied considerably for these applications, as shown in Figure 20 through Figure 23. Achieving a consistent minimum thickness of ccSPF without wasting material is a difficult balance. For this demonstration, the installing contractors were asked to err on the side of too much insulation. Given the high cost of the material, this was often a counterintuitive request. As a mainstream practice, educating the installers on the importance of providing that minimum insulation thickness will be critical to ensure that condensation concerns are mitigated. Proper training and familiarity gained through performing more retrofits is expected to decrease waste and improve consistency.

Figure 18. Exposed duct jacket at the underside of duct

Figure 19. Exposed underside of ductwork not adequately covered with ccSPF

Figure 20. Ductwork well-sealed to sheetrock with ccSPF

Figure 21. Rigid insulation inserted under ductwork to serve as a substrate and provide insulating value

Figure 22. Varying thickness of ccSPF and interference from cross bracing

Figure 23. Varying application thicknesses shown on rectangular (left) and round (right) ducts

4.3 Retrofit Evaluation Summary

As noted in Sections 4.1 and 4.2, the attics in these existing houses were filled with electrical, telephone, and other wiring that crossed the ductwork in many locations. As a result, the wiring was permanently spray foamed to the ceiling and ductwork during the retrofit. If there is a problem with the existing wiring in the house, it might be difficult to service. For buried and encapsulated ducts, however, there might be no practical difference for service technicians trying to deal with wiring buried beneath fiberglass insulation and wiring spray foamed to ductwork. In practice, there was no way to avoid spray foaming over wiring because these wires were so haphazardly laid across the ceiling.

Although the retrofitting methodology included removing ceiling insulation from around the ductwork before applying the spray-foam insulation to the surface of the duct work, there appeared to be no issues with blowback of batt insulation during spray-foam application. Although the airborne fibers associated with blown-in insulation might pose a health and safety problem, the protective equipment worn by the installer is likely sufficient to minimize concern. The authors feel that removing batt insulation before ccSPF application seems unnecessary, except around boots and within a few feet of the ductwork.

A minimal amount of insulation must still be removed around boots to allow access for proper spray-foam adherence to the sheetrock. Similarly, batt insulation can be cut parallel to the ductwork and rolled back a few feet to open 1 to 2 ft of access adjacent to the ducts for proper adherence of the ccSPF to the sheetrock. Any fiberglass remaining below the ductwork can serve as a backer to minimize the amount of ccSPF required for encapsulation. Removing and/or rolling back the fiberglass insulation is unnecessary when a substrate, such as rigid insulation, is inserted beneath the ductwork. A vapor-impermeable insulation of the same insulation level as the spray foam must be used to prevent condensation underneath the duct.

With these strategies for removing existing insulation, it might be possible to minimize costs and site visits by using a two-person crew. While the ccSPF equipment is being set up, a second person can cut back the insulation and expose the boots. After the ccSPF application, the second technician can roll the insulation back into place and cover the boots. Furthermore, preapplying spray-foam insulation around the boots could be unnecessary for preventing leakage into the living space. More testing is needed to see if there is indeed a problem with leakage of ccSPF into the living space. Regardless, this could be undertaken fairly quickly during the field preparation work.

5 Field Monitoring and Performance Testing Results

Field monitoring and performance testing yielded valuable data on the performance of the distribution systems before and after ductwork retrofits. Building specifications obtained by observing the building system and performance testing are discussed and summarized in Section 5.1. Long-term monitoring of occupied buildings reveals valuable information about the thermal performance, as discussed in Section 5.2, and the condensation potential, as discussed in Section 5.3, of the distribution system.

5.1 Building Specifications

All three homes are single-family detached houses of similar vintage with vented attics, slab on grade construction, and attached garages. Table 4 shows building enclosure and mechanical equipment specifications for the three houses. The specifications in the table did not change over the pre- and post-retrofit period.

Pre- and post-retrofit duct, building, and system specifications for variables that change between the pre- and post-retrofit monitoring periods, such as duct leakage and R-value are shown in Table 5. Duct R-values were determined using the methodology outlined in Section 6. Total duct leakage and duct leakage to the outdoors were significantly reduced, and flows stayed relatively constant between the pre- and post-retrofit testing period. Building infiltration was reduced as well through duct sealing, air sealing around duct supply registers, and additional attic insulation.

The post-retrofit supply duct R-value for House 3 is approximately half of the values for the other two homes. The encapsulated duct strategy was used in House 3; houses 1 and 2 received buried and encapsulated ducts. House 3 has comparable post-retrofit duct leakage rates to those observed in House 1. Both have similar duct construction. At House 1, reconfiguration of the ductwork led to an increase in total duct surface area because the duct runs were lengthened to lower ductwork closer to the ceiling plane. At House 2, reconfiguration of the ductwork led to a reduction in supply duct surface area because a circuitous duct board run was replaced with a shorter flex duct run. The return duct surface area was increased because the return ductwork was lengthened to lower ductwork closer to the ceiling plane. All surface areas were measured at the inner duct dimensions.

The pre-retrofit duct leakage numbers for House 2 listed in Table 5 are not entirely accurate. The open duct take-off shown in Figure 12 caused issues with measuring duct leakage before the retrofit. The duct pressure during the total duct blaster test did not reach 25 Pa, and the results were extrapolated from the measured pressure of 15.3 Pa. During the duct leakage to the outside test, the duct and house pressures could not be equalized because of the disconnected duct. The duct leakage to the outside is not reported in Table 5, but for modeling efforts, the duct leakage to the outdoors was assumed to equal the total duct leakage.

Houses 1 and 3 have AHUs placed in the living space, but House 2 has leaky supply and return plenums connected to an AHU in the garage (see Figure 24). As a result, House 2 did not experience a reduction in duct leakage to the outdoors to the same extent as houses 1 and 3. Additional spray foaming of the supply and return ductwork in the garage would have further reduced duct leakages, but this retrofit was outside the scope of this project.

Table 4. Building Enclosure and Space-Conditioning Specifications of Monitored Houses

	House 1	House 2	House 3
Year Built	1991	~1980	1987
Area of Conditioned Space (ft^2)	2,133	2,100	1,876
Volume of Conditioned Space (ft^3)	20,800	18,900	16,289
Bedrooms	4	3	3
Bathrooms	2	2	2
Exterior Finish	Pink stucco	Light wood siding	Light wood siding
Wall Assembly	2 × 4 R-13	2 × 4 R-11	2 × 4 R-13
Ceiling Assembly	R-30 fiberglass batts	R-19 fiberglass batts + 1- to 3-in. blown-in mounds over kitchen	R-19 fiberglass batts
Windows	Double, clear	Single, clear	Double, clear
Skylights	None	Insulated clear, uninsulated light shaft	None
Doors	R-4	R-4	R-4
Main Roof	Dark asphalt 5:12	Light brown asphalt, 5:12	Light brown asphalt 5:12
Outdoor Unit Model Number	Payne PH15NB048-A	Tempstar NHP042AKAI	Payne PH10JA036-C
Outdoor Tonnage	4 tons	3.5 tons	3 tons
Indoor Unit Model Number	Payne PF4MNA061	Trane TWE042C1FC	PF1MNA036
Indoor Tonnage	5 tons	3.5 tons	3 tons
Rated Energy Efficiency Rating/Seasonal Energy Efficiency Ratio	12.0/14.5	8.8/10.0	9.05/10.00
Cooling Capacity (Btu/h)	47,500	39,500	34,000
High-Temperature Heating (Btu/h)	46,500	38,000	34,000
Low Temperature Heating (Btu/h)	29,200	22,000	20,600
Number of Compressor Speeds	1	1	1
Control Type	Thermostatic	Orifice	Orifice
AHU Fan Type	Permanent split capacitor	Permanent split capacitor	Electronically commutated motors

Table 5. Pre- and Post-Retrofit Duct, Building, and System Specifications

	House 1		House 2		House 3	
	Pre-Retrofit	Post-Retrofit	Pre-Retrofit	Post-Retrofit	Pre-Retrofit	Post-Retrofit
Supply Duct Surface Area (ft^2)[a]	339	374	384	369	214	214
Return Duct Surface Area (ft^2)[b]	N/A	N/A	163	194	N/A	N/A
Supply Duct Effective R-Value (h-ft^2-°F/Btu)	4.7	21.9	6.5	26.1	4.6	11.1
Return Duct Effective R-Value (h-ft^2-°F/Btu)	N/A	N/A	4.9	26.2	N/A	N/A
Flow at Operating Conditions (cfm)	1,562	1,469	1,144	1,138	949	976
Duct Leakage to Outdoors (cfm@25 Pa)	152	29	N/A[b]	162	88	22
Total Duct Leakage (cfm@25 Pa)	527	188	382[c]	290	227	117
Building Infiltration (cfm@50 Pa)	2,672	2,138	4,066	2,905	2,306	2,168

[a] Duct surface area is measured at the inner duct dimensions.
[b] Duct leakage to the outdoors could not be measured because of disconnected duct take-off.
[c] Total duct leakage was measured at 15.3 Pa and extrapolated to 25 Pa.

Figure 24. AHU at House 2 located in garage with leaky return and supply plenums

Using the data displayed in Table 4 and Table 5, pre- and post-retrofit building loads were calculated using ACCA's *Manual J: Residential Load Calculation* (2006), as shown in Figure 25 and Figure 26. At House 1, the building loads are similar to the installed capacity, and the HVAC system seems to be properly sized. At House 2, the installed capacity is drastically undersized compared to the calculated building loads. Monitoring revealed long run times for the equipment in House 2, supporting the calculation that the system is undersized. The large loads are primarily caused by the poor window system installed in the house. House 3 Manual J calculations show that the system is slightly oversized.

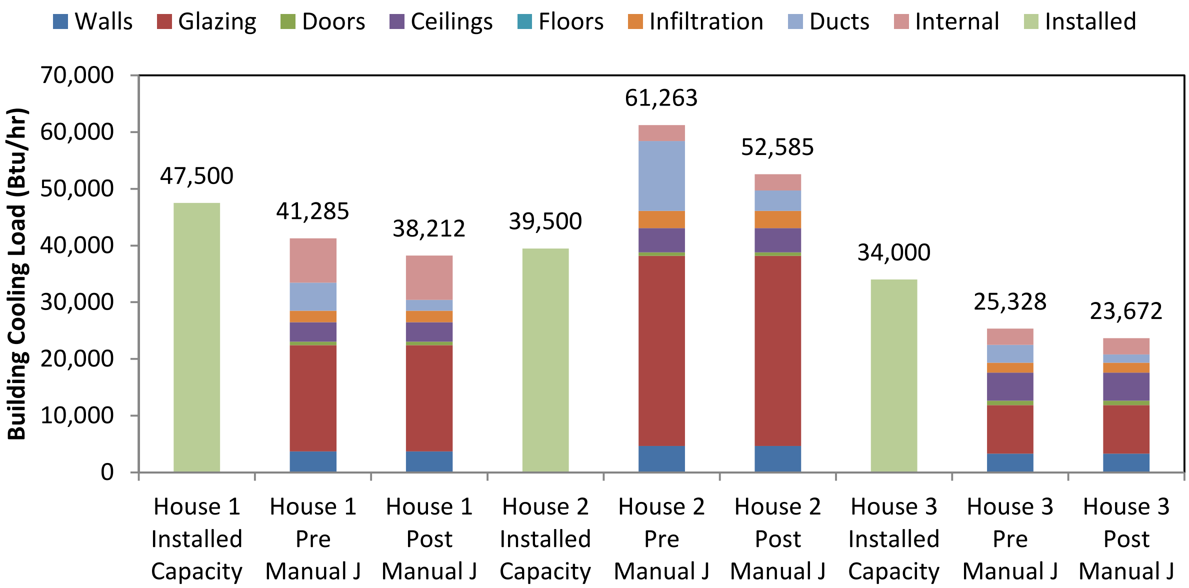


Figure 25. Pre- and post-retrofit Manual J building cooling loads compared to installed capacity

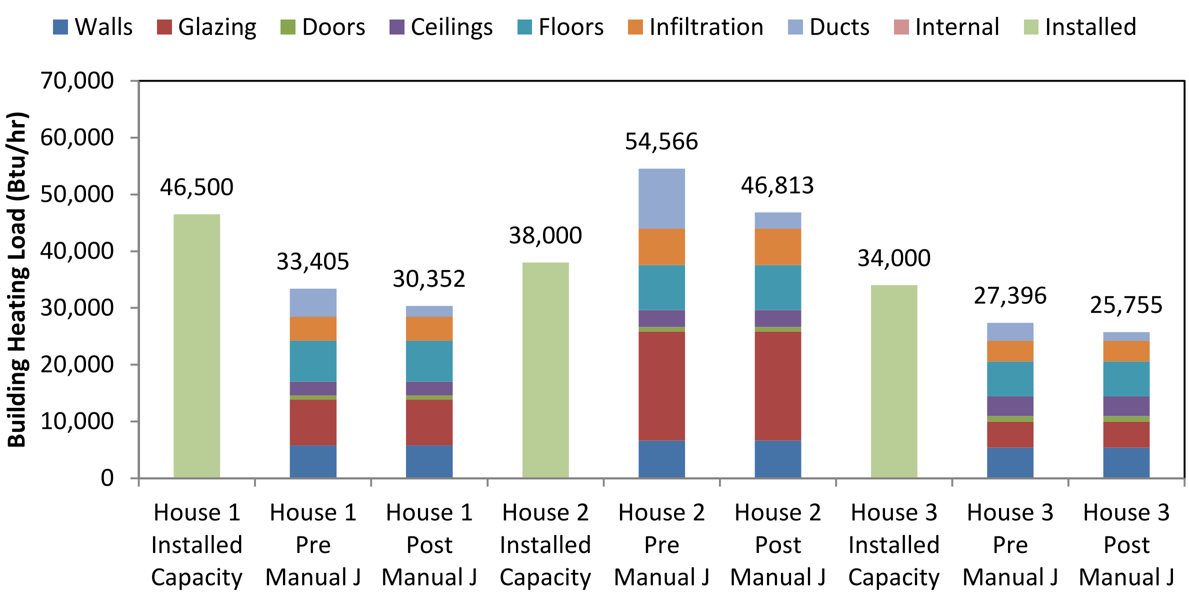


Figure 26. Pre- and post-retrofit Manual J building heating loads compared to installed capacity

5.2 Qualitative Discussion of Thermal Performance

Changes in the mechanical and distribution system configuration and operation at each house created challenges for interpreting long-term field monitoring and performance testing data. House 1 was unoccupied and the cooling system was set to a higher set-point temperature during the post-retrofit period. At House 2, a large hole in the ductwork was discovered during the retrofit, which complicated the comparison between pre- and post-retrofit performance. At House 3, the outdoor condensing unit was cleaned and recharged with refrigerant between the pre- and post-retrofit periods, which increased the system's efficiency. The ambient temperature sensor was placed too close to the condensing unit to measure temperatures accurately. Despite these challenges, the data shown in Figure 27 through Figure 32 give interesting insights into the benefits of buried ducts.

The graphs each show a 1-day period for a typical duct at each house over a typical summer day. The day selected starts at 4 a.m. on July 29 of the year during which the home was monitored. Two graphs are shown for each house, enabling a comparison of the pre- and post-retrofit performance of the same duct run. Periods of air-conditioning operation can be identified in these graphs by looking at the discharge airstream temperature (shown as the light blue line). During periods of air-conditioning operation, the discharge temperature drops significantly, typically to below 60°F. Table 6 lists the weather conditions for the two days graphed in this section using data available from the National Climactic Data Center (NCDC).

Table 6. Weather Conditions for Days Graphed in This Section

	July 29, 2010	July 29, 2011
High	96°F	94°F
Low	73°F	73°F
Dew Point	72°F	72°F
Clouds	Clear/partly cloudy with afternoon thunderstorms	Clear/partly cloudy with afternoon thunderstorms

Source: NCDC (2012).

The pre-retrofit graphs confirm that the equipment in houses 1 and 3 can satisfy the cooling loads because the systems cycle on and off. House 2, however, has an undersized system, and as a result, the cooling system runs constantly between 10:00 a.m. and 8:00 p.m. Post-retrofit run time cannot be assessed at House 1 because of a change in occupancy. The run time at House 3, however, shows an increase in cycling caused by a reduction in load corresponding to the retrofit. This increase in cycling, though, could be partially caused by the cleaning and recharging of the mechanical system that took place before the post-retrofit monitoring started. At House 2 with its undersized system, no reduction in load is observable through system run time.

As expected, the additional insulation applied to the ductwork results in a significant reduction in the temperature of the duct jacket surface. The temperature of the duct jacket surface during the pre-retrofit period decreased substantially when the air-conditioning system was running. By contrast, the surface temperature of the ccSPF surface during the post-retrofit period fluctuates only slightly during air-conditioner operation. This vast difference in temperature sensitivity of the ductwork surface points to a large increase in the R-value of the ductwork.

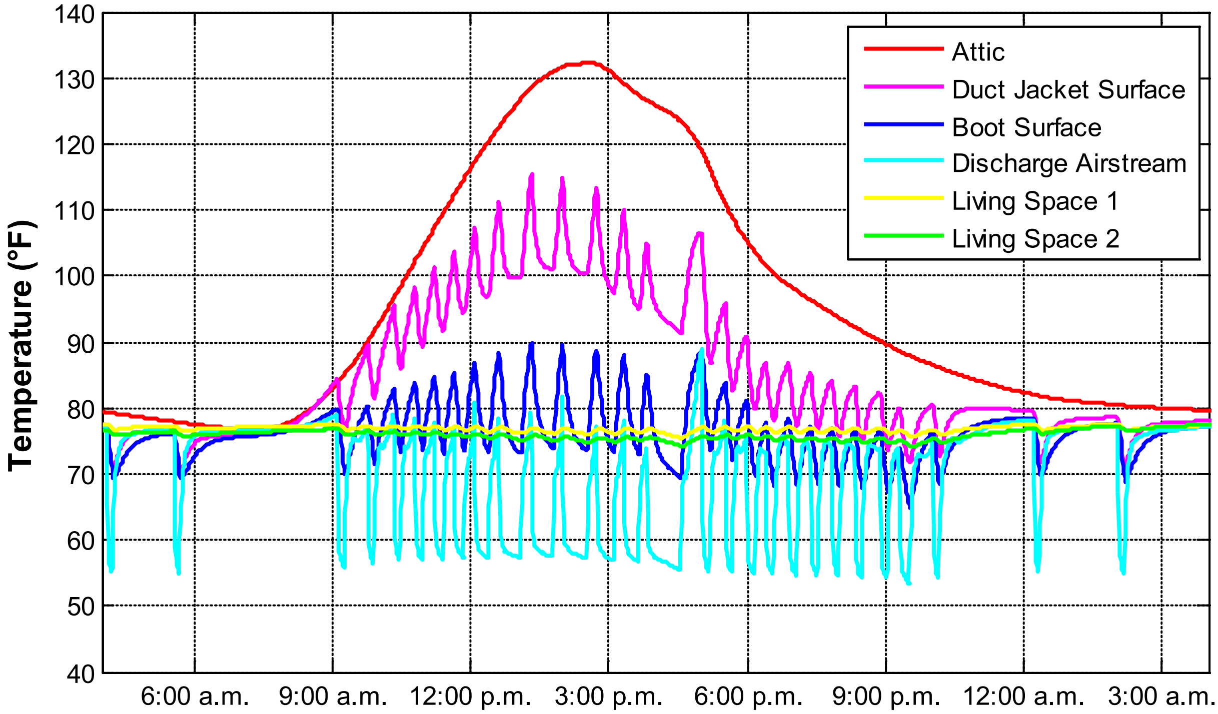


Figure 27. Pre-retrofit surface and air temperatures at duct run 2 in House 1

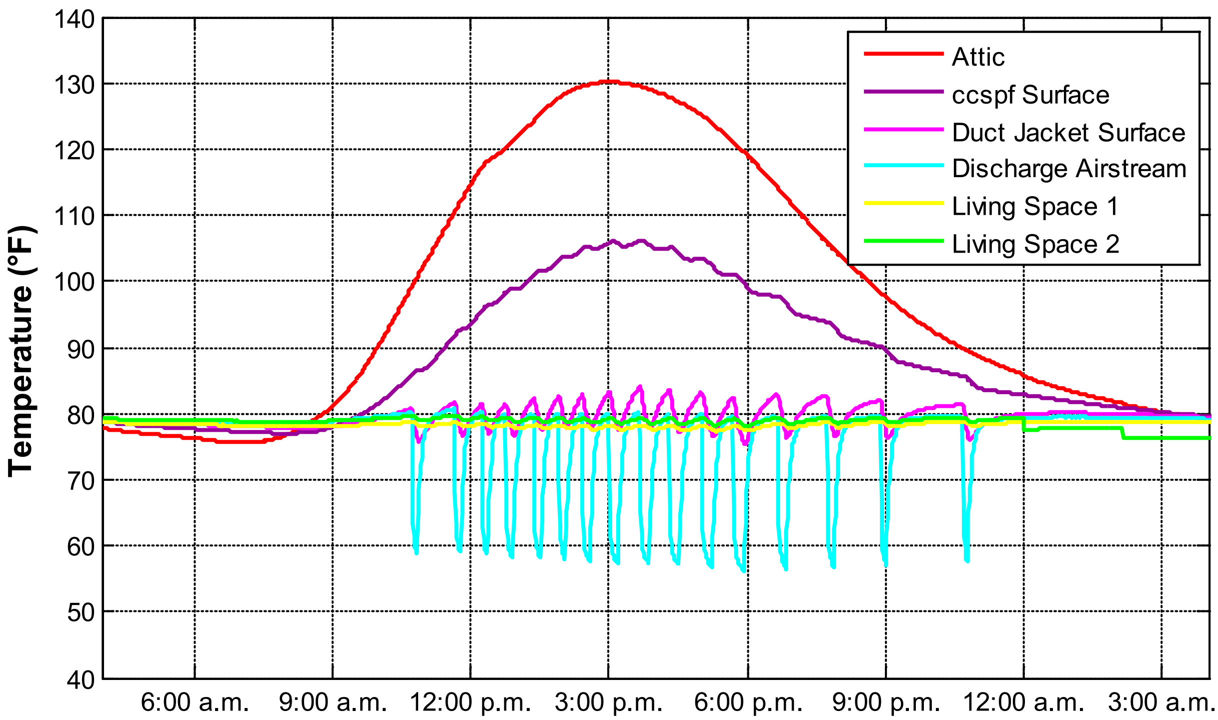


Figure 28. Post-retrofit surface and air temperatures at duct run 2 in House 1

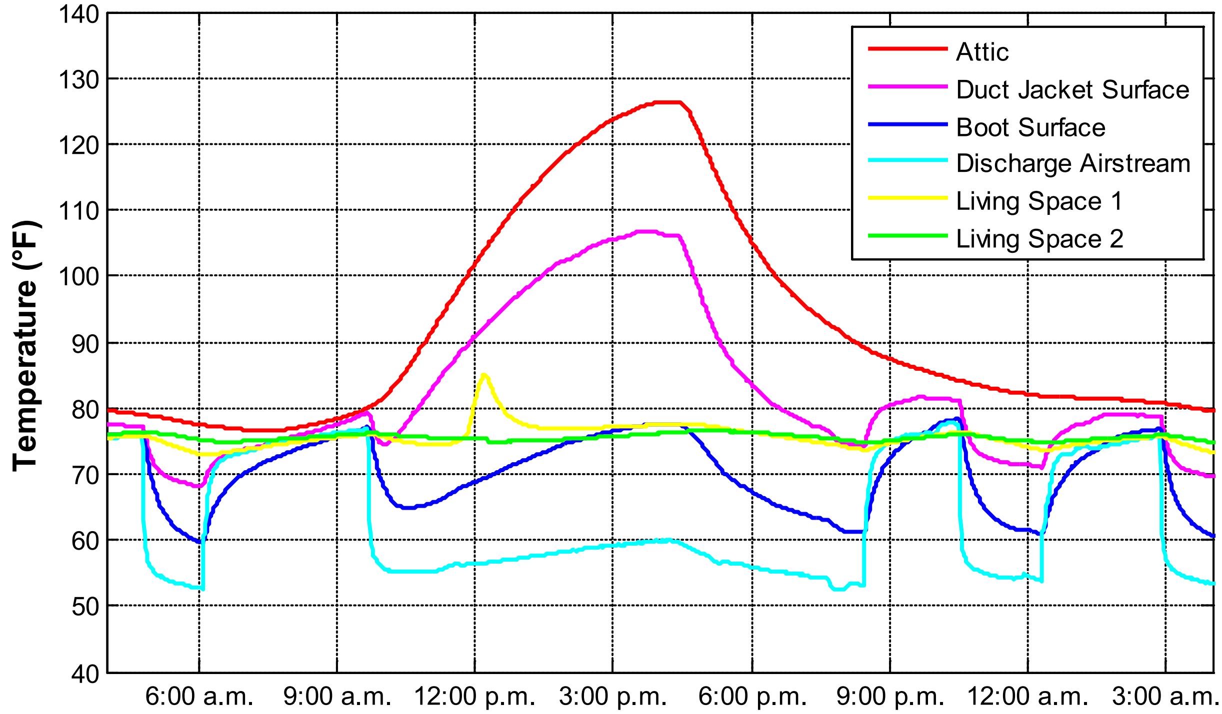


Figure 29. Pre-retrofit surface and air temperatures at duct run 3 in House 2

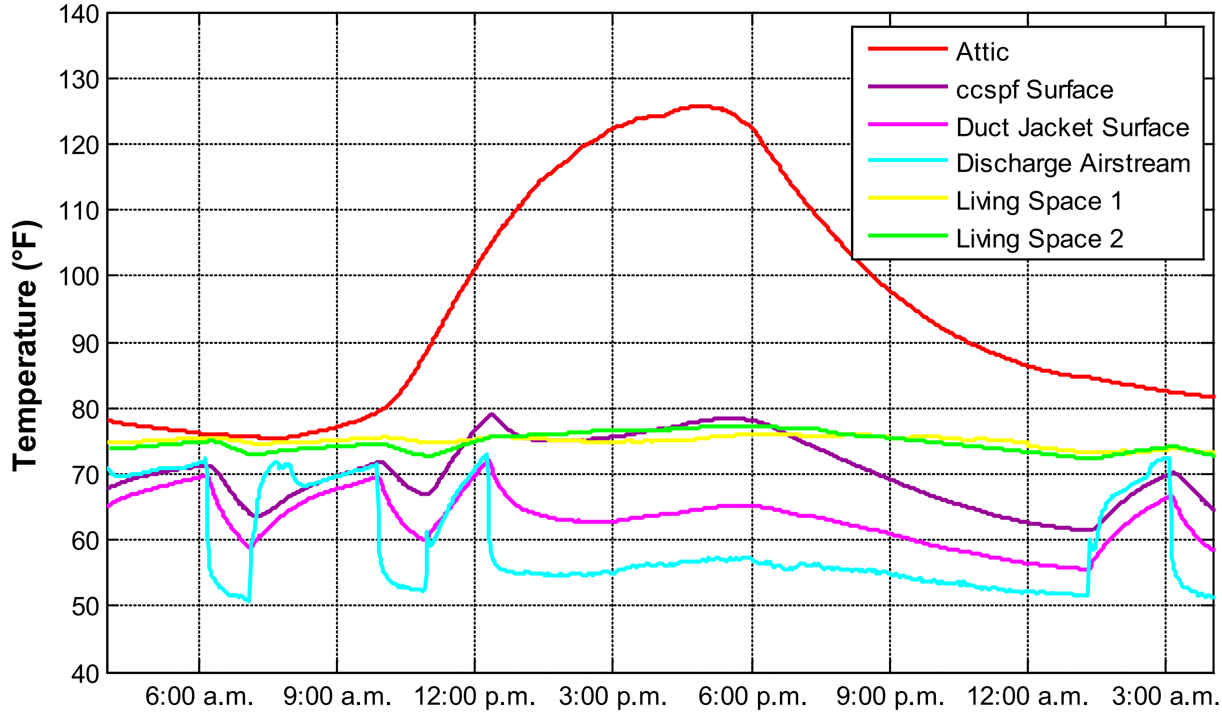


Figure 30. Post-retrofit surface and air temperatures at duct run 3 in House 2

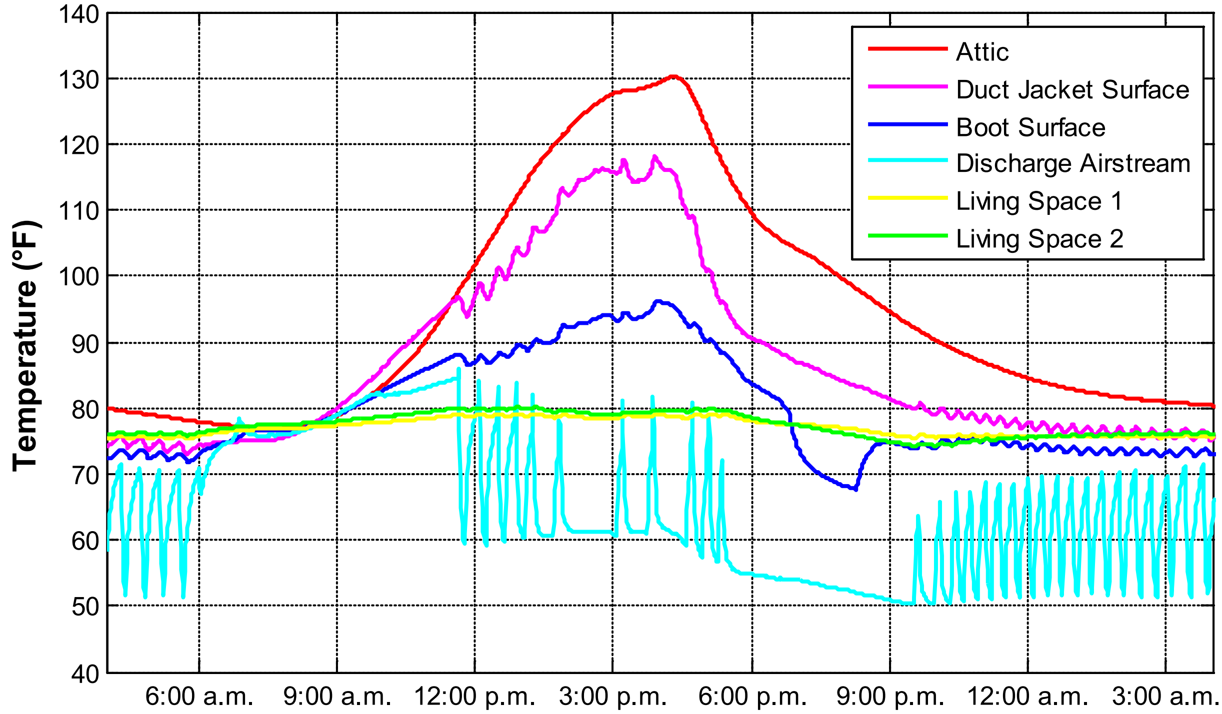


Figure 31. Pre-retrofit surface and air temperatures at duct run 2 in House 3

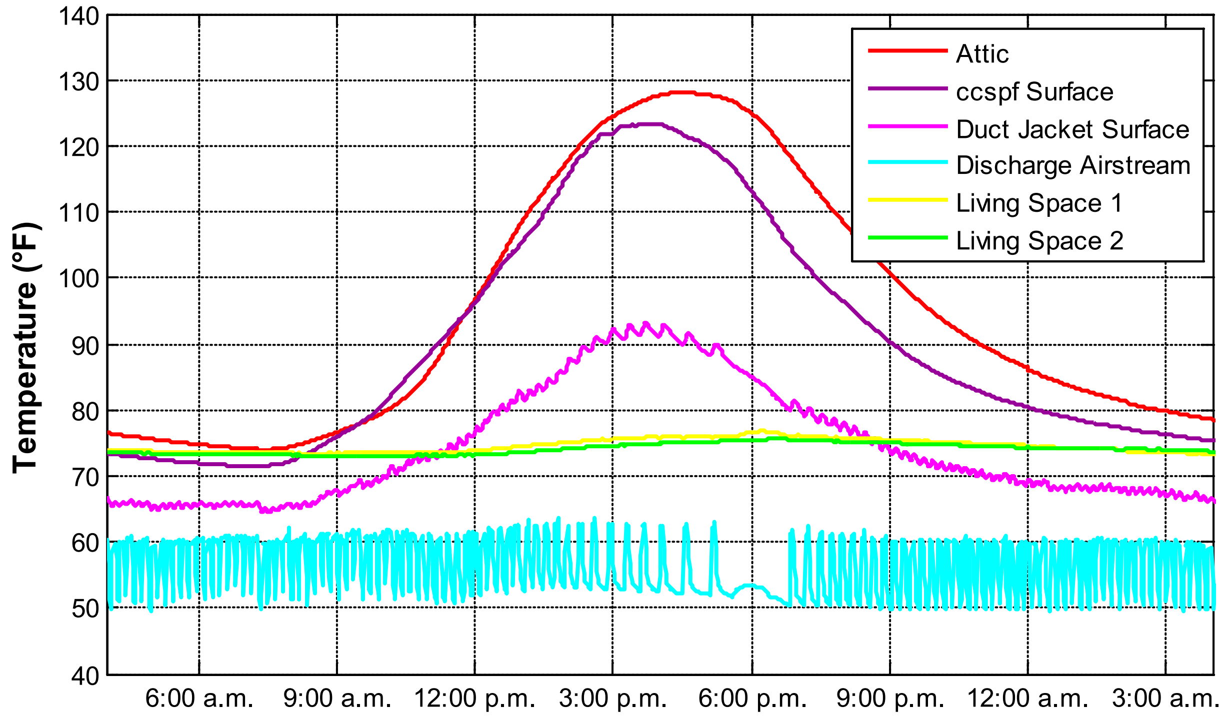


Figure 32. Post-retrofit surface and air temperatures at duct run 2 in House 3

For House 3, the encapsulated ducts were not buried. Comparing the post-retrofit duct surfaces in House 3 to those of similar construction in House 1, duct jacket and ccSPF surface temperatures are much higher for the unburied case than for the buried case. Unlike the other two houses, the temperature of the duct jacket surface in House 1 remains coupled with the temperature of the attic. The pre- and post-retrofit comparison for House 1, however, shows a significant decrease in the duct jacket surface temperature. The ccSPF surface temperature profile is similar to that of the pre-retrofit duct surface but with far less variation related to system cycling.

Infrared thermal imaging of the pre- and post-retrofit ductwork further validates the large increases in duct R-values and reductions in duct leakage. Figure 33 and Figure 34 compare thermal images of the pre-retrofit ductwork at House 2 with the same ductwork after encapsulation but before burial. Large thermal losses occur in both cases.

With the AHU operating in cooling mode, the surface temperature of the ductwork before the retrofit was significantly lower than that of both the surrounding air and the encapsulated ductwork. The temperature of the exterior surface of the duct board was approximately 65°F in Figure 33. After encapsulation, the surface of the ccSPF is just under 100°F in Figure 34. As demonstrated by the previous graphs, the thermal imaging confirms the duct surface temperature has become nearly completely decoupled from the airstream temperature and more closely aligns with the ambient attic temperature.

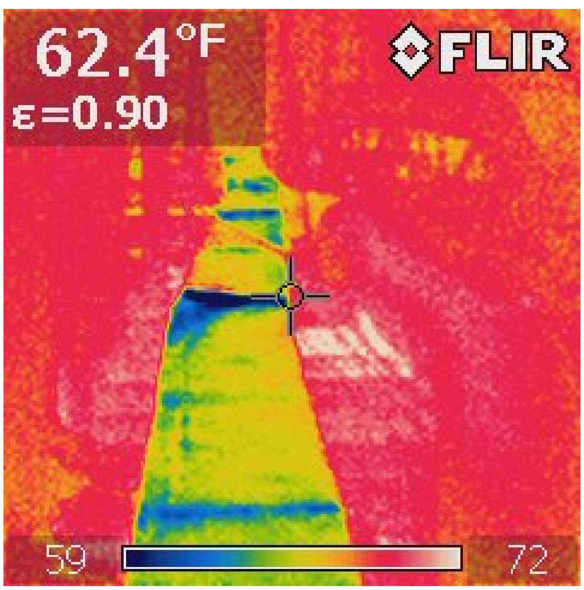


Figure 33. Pre-retrofit infrared thermal imaging at House 2

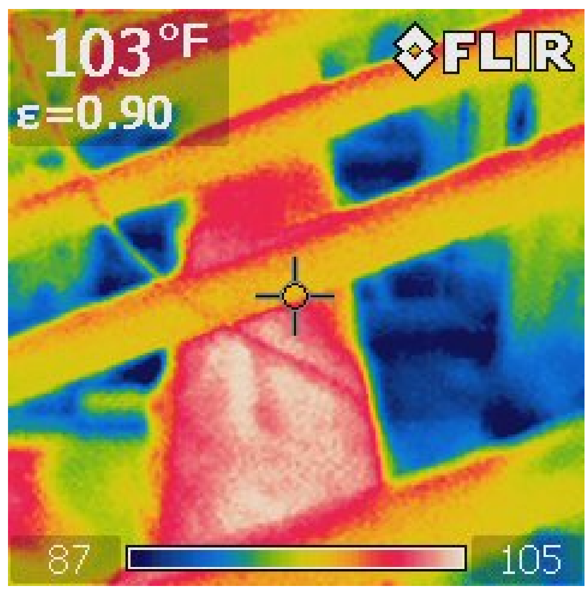


Figure 34. Infrared thermal imaging of encapsulated ductwork at House 2

This conclusion is further supported by less direct observations of the field monitoring data. During the pre-retrofit monitoring, the discharge airstream temperatures were observed to rise above the temperature of the living space during periods when the air conditioner was not running. As a consequence, when the air conditioner turned on, the volume of hot air inside the ductwork was pushed back into the living space, resulting in an increased load on the house.

Following the duct retrofits, the measured discharge air temperature was observed to stay at or below the living space temperature, eliminating this problem.

Pushing this volume of hot, unconditioned air into the living space undoubtedly increases the cooling load of the building, but quantifying the degree to which the cooling load is increased is difficult and cannot be accomplished using the data collected in this field study. Although monitoring was not conducted during the heating season, this retrofit is expected to also mitigate a similar heating load penalty. In new construction homes that use buried and encapsulated ducts, this peak load reduction benefit is typically accounted for by downsizing the equipment.

5.3 Qualitative Discussion of Condensation Potential

Graphs of duct surface temperatures and attic dew points reveal some interesting information about the condensation potential of the pre- and post-retrofit ductwork (Figure 35 through Figure 40). When the surface temperature of the duct falls below the dew point of the surrounding air, there is a potential for condensation on the duct. In practice, it is often difficult to accurately measure the relative humidity of the surrounding air, and the attic ambient air can be used as a proxy for the surrounding air. In reality, however, the dense insulation retards moisture transfer from the attic air to the duct surface. Although Chasar and Withers (2012) partially validated the use of attic dew point temperatures and duct surface temperatures to measure condensation potential, more detailed modeling of the hygrothermal performance of buried ducts was performed in this study to accurately evaluate the condensation potential of a buried duct installation (see Section 9).

The graphs in Figure 35 through Figure 40 reveal the change in condensation potential between the pre- and post-retrofit cases. The graphs show a 24-h period for each house for a typical summer day. These periods are identical to those shown in the graphs in Section 5.2. Two graphs are shown for each house, comparing the pre- and post-retrofit performance. In the pre-retrofit case, the attic dry bulb and dew point temperatures are plotted on each graph. This is overlaid with three boot surface temperature measurements on the left axis (solid lines) and three corresponding boot surface relative humidity measurements on the right axis (dashed lines). In the post-retrofit case, the surface temperatures and relative humidities are reported for the top surface of the ccSPF. The difference in graphed locations is caused by the selection of monitoring locations during the pre- and post-retrofit periods. The potential for condensation occurs when any of the three boot surface or ccSPF temperatures fall below the black line that represents the attic dew point temperature.

At first glance, the attic dew point temperatures fluctuate significantly compared to the outdoor dew point, raising questions about the validity of the attic dew point temperature measurements. Although the mean ambient dew point temperature corresponding to the 1% design temperature at Jacksonville Naval Air Station is 70°F (ASHRAE 2009), the dew points in these attics reach into the upper 80s. Furthermore, even though the ambient dew point is relatively constant throughout the day, the attic dew point in these houses drops to around 60°F during the night and rises rapidly into the upper 80s during the day. Although the behavior of the attic air is intriguing and cannot be easily explained, the attic dew point temperatures measured in this study do not seem to be inaccurate. The relative humidity sensors used in this study are accurate in the hot attic conditions, and the dew point calculations used in data postprocessing have been rigorously verified. Furthermore, a long-term monitoring study that included 20 houses in Florida (Arena et al. 2010) and a study of an early 1990s vintage home in Florida (Chasar and Wither 2012) found similar trends in attic dew point temperatures. Appendix A contains a more comprehensive discussion of this issue.

The pre-retrofit cases at all three houses showed a potential for condensation at the boot surface. Since significant amounts of condensation would likely stain the ceiling gypsum board, it was assumed that any accumulated condensation was minimal and/or able to dry out. Uncontrolled air leakage at the boot, which allows conditioned air to escape into the attic through unsealed gaps around the boot, could have resulted in the unintentional benefit of mitigating the condensation issues, similar to the results observed by Griffiths et al. (2002). The high potential of condensation observed in the pre-retrofit case is validated by the high relative humidities observed at the surface of the ductwork. These relative humidities approach saturation and the relative humidity sensors lose accuracy at these levels.

As anticipated, the post-retrofit case at houses 1 and 3 showed no condensation potential at the surface of the ccSPF applied directly over the entire boot. The surface temperatures were significantly higher than the attic dew point. The temperature sensors in the pre-retrofit case were placed on the boot and therefore represent the worst-case scenario. In the post-retrofit case, however, the sensors were usually placed at the top of the ductwork on the surface of the ccSPF, which raises some questions about the condensation potential at other points along the ductwork profile.

Surprisingly, the encapsulation and burial of the ductwork at House 2 did not mitigate the existing condensation potential of the pre-retrofit ductwork. As in the pre-retrofit case, it was assumed that any accumulated condensation was minimal and/or able to dry out because significant amounts of condensation would likely stain the ceiling gypsum board. Although the exact cause of the post-retrofit condensation potential is unknown, it is possible that the long run time of the undersized system resulted in lower surface temperatures.

Based on previous research, the 1.5 in. of ccSPF was applied to the ducts specifically to mitigate the condensation potential, regardless of the additional R-value provided by any additional insulation. The post-retrofit results for House 3, in which the ducts were not buried, can be contrasted with the results from the buried ducts in House 1. At House 3, the encapsulated duct surface temperature profiles aligned closely with the ambient attic conditions. At the boot locations shown in the figures, all measurements were taken beneath the layer of existing attic insulation. The temperature differential between the boot surface and attic ambient was larger in House 1, where blown-in insulation was added.

Before the retrofit, the low temperatures and high relative humidities at the boot surfaces in House 1 showed a high condensation potential. These issues appear to have been mitigated with the buried and encapsulated duct approach. At House 2, the boot surface temperatures were lower than the dew point of the attic air in the pre-retrofit case. The relative humidity of the air at the surface of the duct, however, was significantly below saturation, and as a result, the condensation potential was low. In the post-retrofit case, the condensation potential was not worsened by the further burial of the ductwork.

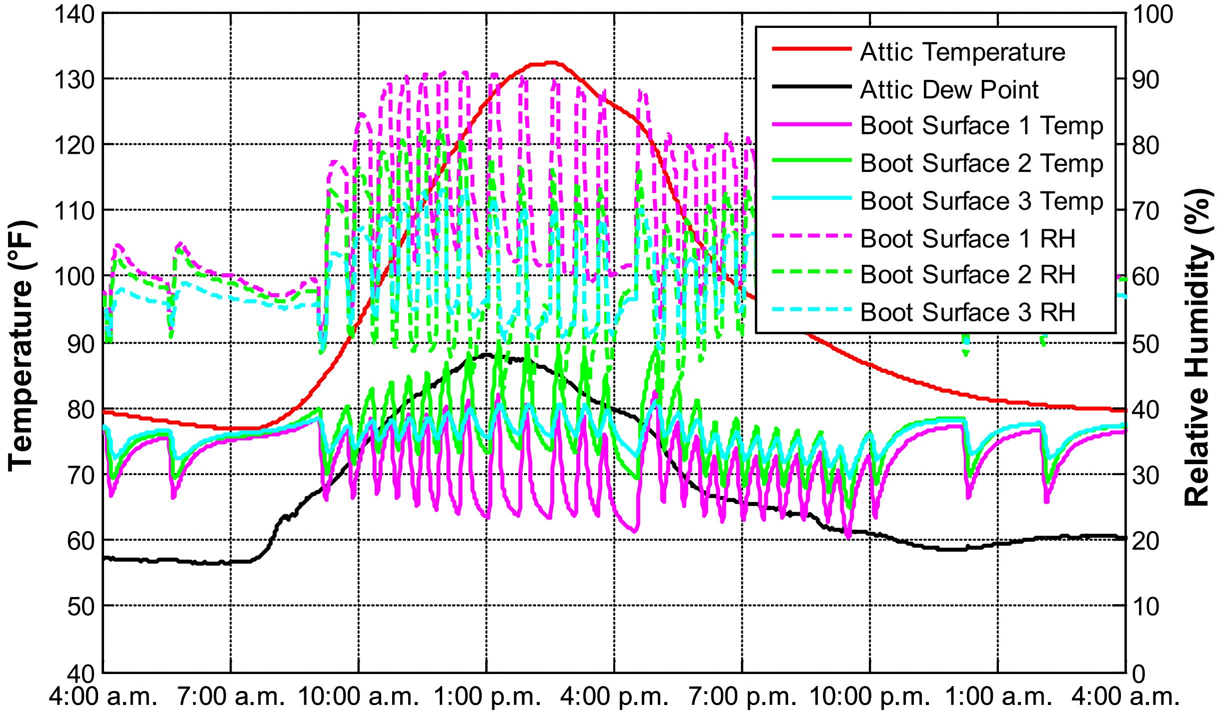


Figure 35. Pre-retrofit boot surface temperatures and attic dew point at House 1

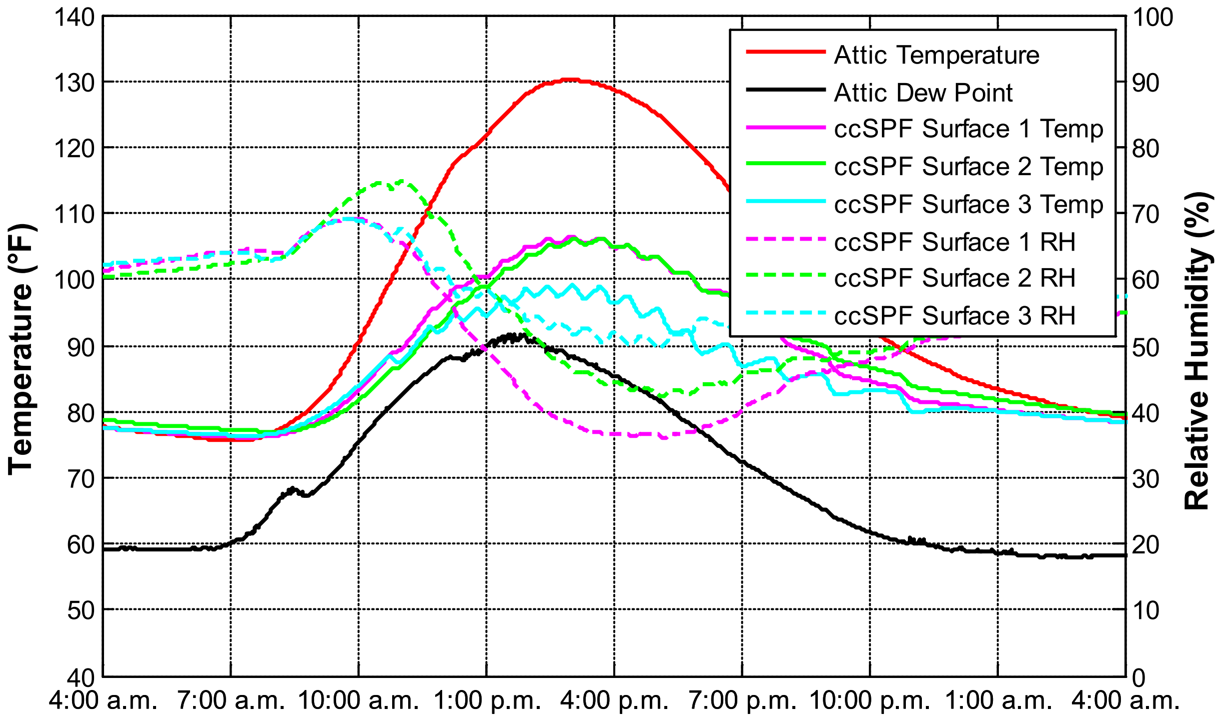


Figure 36. Post-retrofit ccSPF surface temperatures and attic dew point at House 1

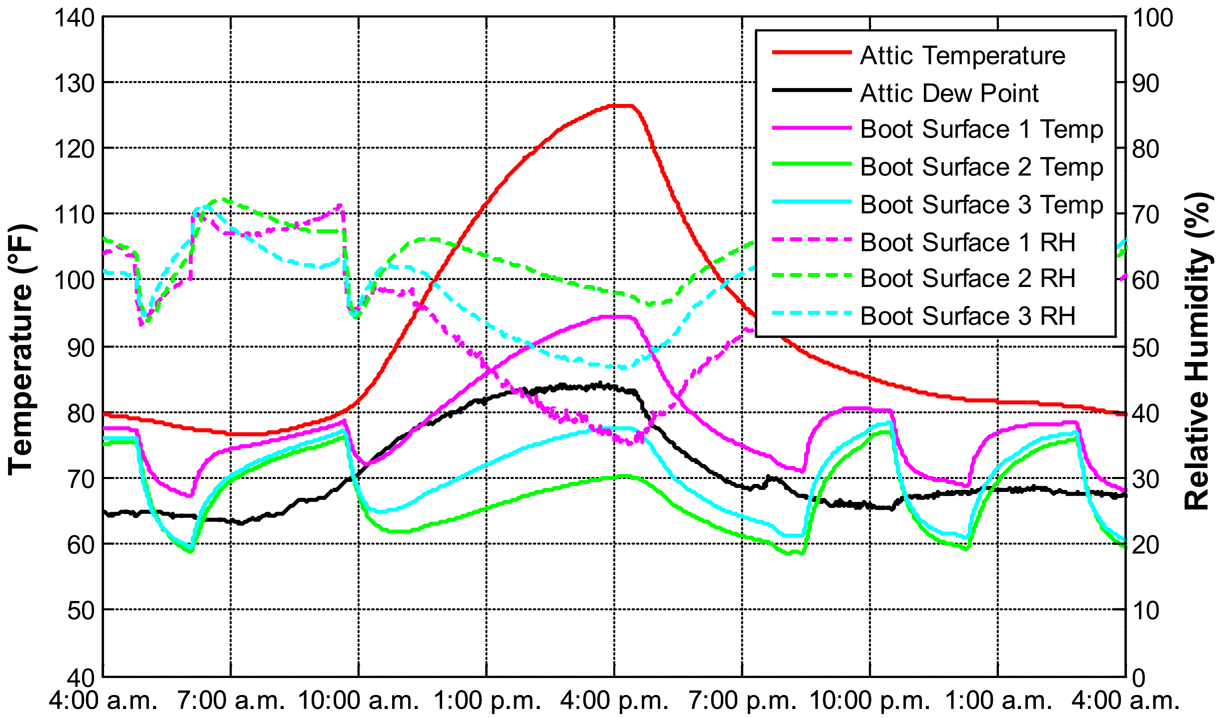


Figure 37. Pre-retrofit boot surface temperatures and attic dew point at House 2

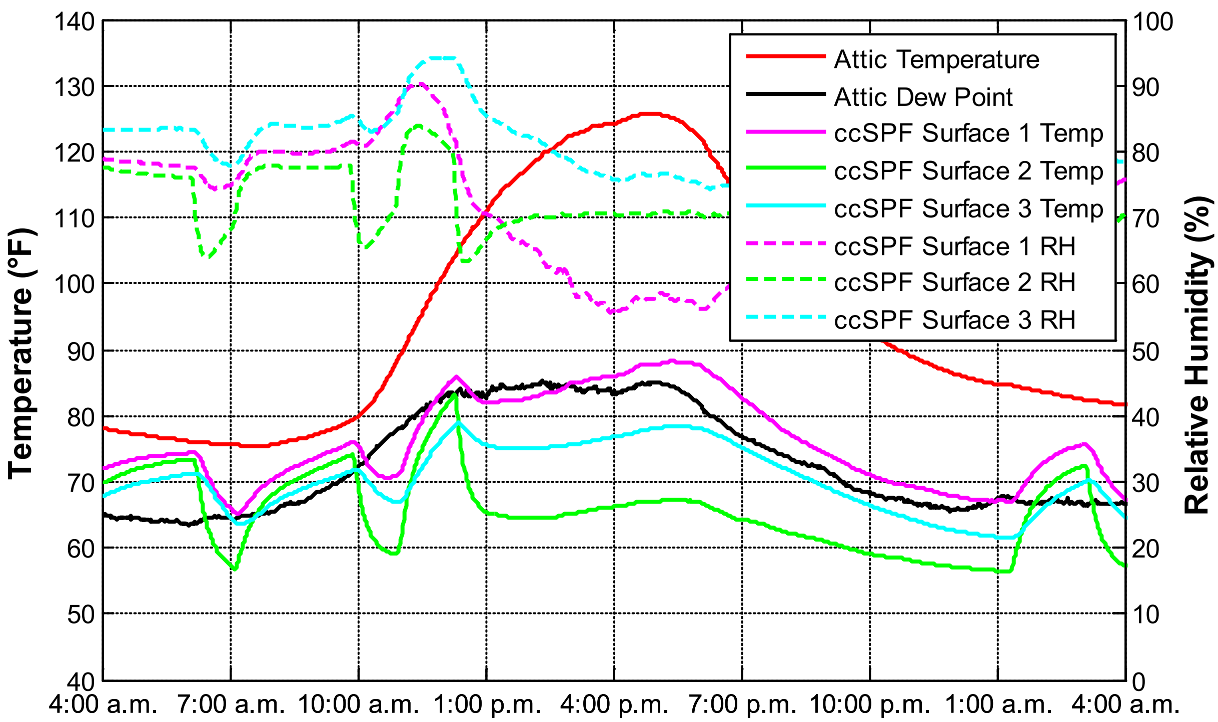


Figure 38. Post-retrofit ccSPF surface temperatures and attic dew point at House 2

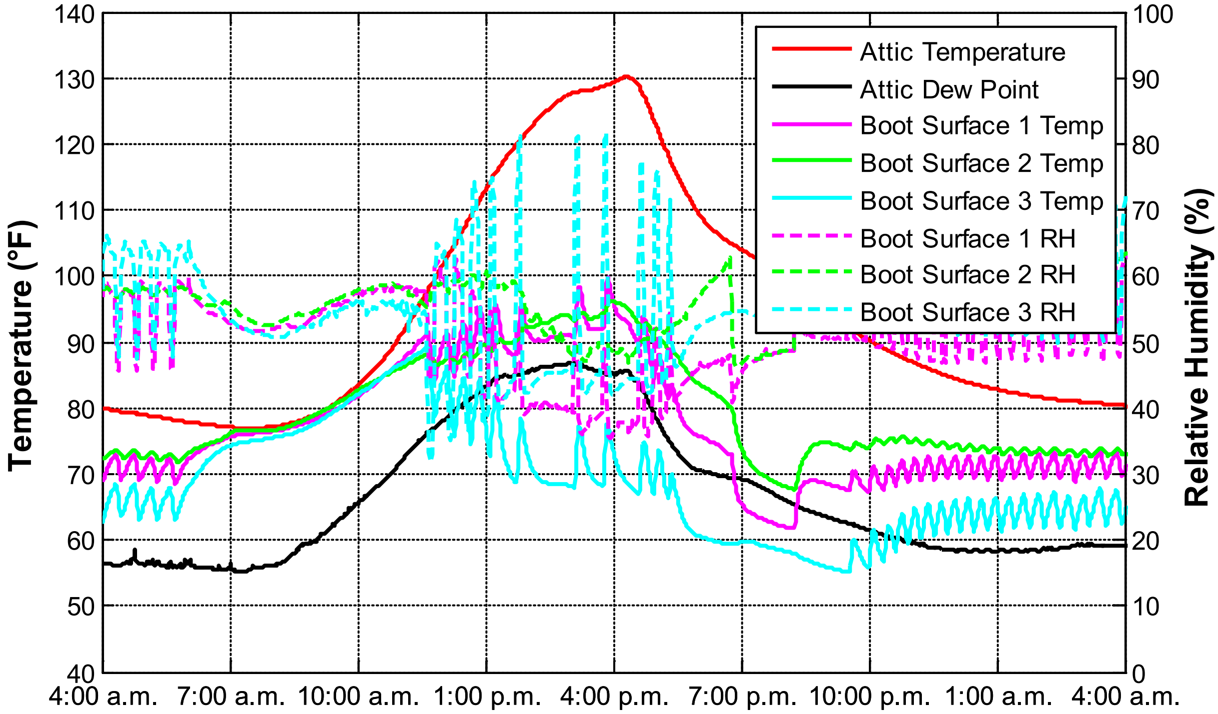


Figure 39. Pre-retrofit boot surface temperatures and attic dew point at House 3

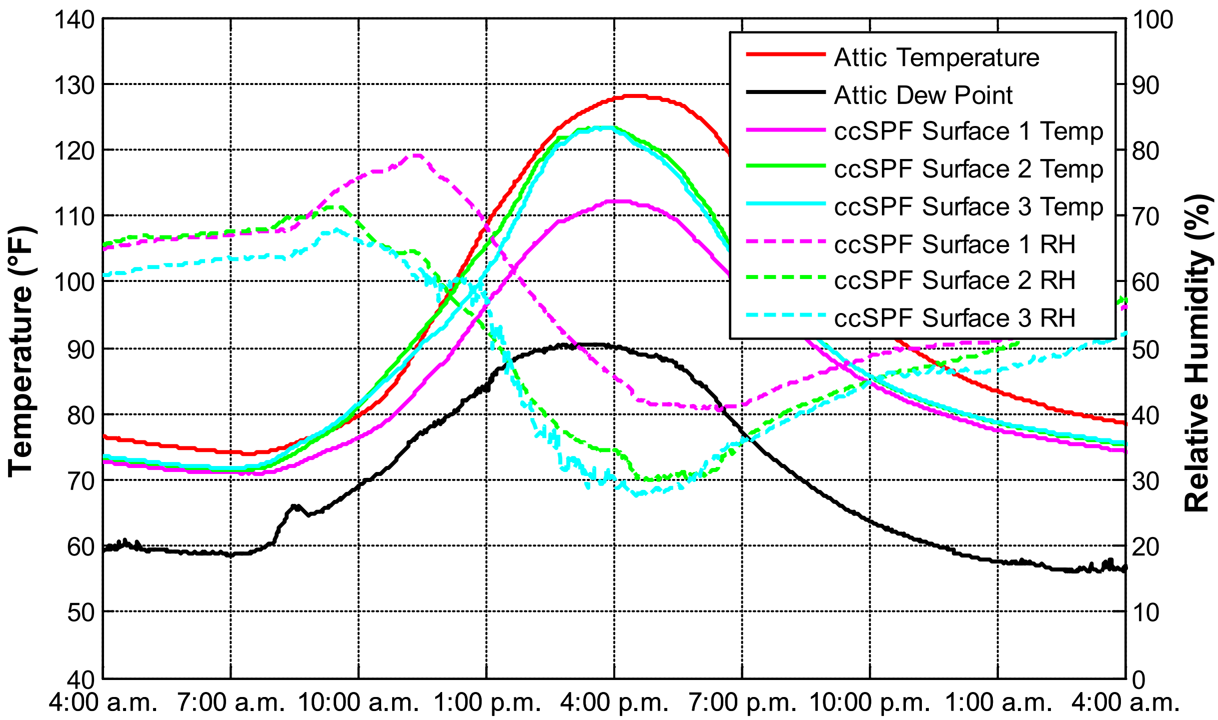


Figure 40. Post-retrofit ccSPF surface temperatures and attic dew point at House 3

6 Theoretical Effective and Apparent R-Values of Round Ductwork by Insulation Strategy

Observations of the field demonstration gave the team valuable insight into the feasibility of this retrofit strategy. As part of the field work, researchers identified barriers, collected performance data, and assessed concerns associated with condensation potential. Installed retrofit costs were also estimated based on the contractor costs for these retrofits (Section 10). The next critical step was to determine the potential energy savings and, ultimately, the cost effectiveness associated with the retrofit strategy. This was done through a combination of analytical calculations and modeled analysis.

Knowing effective R-values, which *exclude* heat transfer between the ductwork and the conditioned space, is necessary to calculate energy savings associated with encapsulated and buried and encapsulated ducts. Apparent R-values, which *include* heat transfer between the ductwork and the conditioned space, are also useful for comparing experimental results to theoretical calculations. Effective and apparent R-values can be calculated using Equations 1 and 2, respectively [8]

$$R_{effective} = \frac{2\pi r_i \Delta \mathrm{T}}{\mathrm{Q}_{\mathrm{attic}\rightarrow duct}} \quad (1)$$

$$R_{apparent} = \frac{2\pi r_i \Delta \mathrm{T}}{\mathrm{Q}_{\mathrm{attic}\rightarrow duct} + Q_{interior\rightarrow duct}} \quad (2)$$

where

$Q_{attic\rightarrow duct}$	=	the heat transfer between the attic and duct
$Q_{interior\rightarrow duct}$	=	the heat transfer between the interior space and duct
r_i	=	duct inner radius
ΔT	=	temperature difference between duct and attic.

Both effective and apparent R-values of round ductwork were calculated using either analytical or computational methods for four insulation strategies:

- **Traditionally insulated ducts** are insulated with traditional fiberglass duct wrap with rated R-values of 4.2, 6, and 8.
- **Encapsulated ducts** are traditionally insulated ducts encapsulated in a layer of ccSPF insulation. These ducts have higher R-values and lower leakage rates than traditionally insulated ducts.
- **Buried ducts** are traditionally insulated ducts buried beneath loose-fill insulation at the ceiling plane. These ducts have higher R-values, but only slightly lower leakage rates, than traditionally insulated ducts.

[8] In this report, all thermal resistance values *R* are given as totals of the entire depth of the application in units of h-ft^2-°F/Btu. Conductivities *k* are given as the reciprocal of the R-values per inch in units of Btu-in./h-ft^2-°F. As a result, R-values should be considered the total of the application, and conductivities are the values per inch of application.

- **Buried and encapsulated ducts** are traditionally insulated ducts encapsulated in a layer of ccSPF insulation and buried beneath loose-fill insulation at the ceiling plane.

R-values of traditionally insulated ducts were calculated to accurately compare pre- and post-retrofit performance using similar assumptions. R-values of buried ducts were calculated to compare the methodology used in this study to that of previous studies on buried ducts. The methodology used to calculate the traditional and buried duct insulation strategies also served as the basis for the R-value calculations of encapsulated and buried and encapsulated ducts.

Since traditionally unburied ducts do not experience heat transfer with the conditioned space, apparent and effective R-values are equivalent (i.e., the heat transfer between the duct interior and the attic will equal heat losses measured under laboratory or field testing). These R-values can be calculated analytically in a closed-form equation. Buried ducts have different effective and apparent R-values, which must be computed using numerical methods. The next two sections outline the analytical calculations of traditional and encapsulated ductwork, followed by two sections that outline the modeled analysis for buried and buried and encapsulated ducts.

6.1 Traditionally Insulated Round Ductwork

When installed over round ductwork, the effective R-value of the insulation application does not equal the nominal R-value of the insulation. R-values per inch are rated for a material lying flat, and when accounting for the cylindrical installation of the geometry, effective R-values can be significantly different from the nominal values. Furthermore, the nominal R-value excludes the inner and outer surface films of air (Palmiter and Kruse 2006). The effective R-value of the ductwork $R_{effective}$ in relation to the inner area of the ductwork is the sum of the inner surface film resistance R_{inner}, the actual R-value of the cylindrical insulation $R_{insulation}$, and the outer surface film resistance R_{outer}, corrected for the ratio of the outer diameter d_o to the inner diameter d_i.

$$R_{effective} = R_{inner} + R_{insulation} + \frac{d_i}{d_o} R_{outer} \quad (3)$$

Palmiter and Kruse (2006) found that the inner surface film resistance is dependent on duct inner diameter and the exterior surface film is independent of inner diameter. For this analysis, Palmiter and Kruse's inner surface film resistances (see Table 7) and a slightly different outer film heat transfer coefficient of 1.76 Btu/h-ft^2-°F, to be consistent with previous buried duct research, was used. Palmiter and Kruse further determined that the actual R-value of the ductwork can be found as a function of the rated R-value $R_{nominal}$, the inner diameter of the duct d_i, and the outer diameter of the duct d_o.

$$R_{insulation} = \frac{d_i}{d_o - d_i} R_{nominal} \ln\left(\frac{d_o}{d_i}\right) \quad (4)$$

Based on the modified outer surface film resistance, the effective R-values of round insulated ducts found for various insulation levels are shown in Table 8.

Table 7. Inner Surface Film Resistances by Duct Inner Diameter

Duct Inner Diameter (in.)	Inner Surface Film Heat Transfer Coefficient (Btu/h-ft^2-°F)
4	2.22
6	2.04
8	1.92
10	1.85
12	1.79
14	1.72
16	1.69

Table 8. Effective R-Values of Round Insulated Flexible Ducts

Duct Inner Diameter (in.)	R-4.2 Thickness = 1.25 in.		R-6.0 Thickness = 1.79 in.		R-8.0 Thickness = 2.38 in.	
	$R_{insulation}$	$R_{effective}$	$R_{insulation}$	$R_{effective}$	$R_{insulation}$	$R_{effective}$
4	3.3	4.1	4.3	5.0	5.3	6.0
6	3.5	4.4	4.7	5.6	5.9	6.7
8	3.7	4.6	5.0	5.9	6.3	7.2
10	3.8	4.7	5.1	6.1	6.5	7.5
12	3.8	4.9	5.3	6.3	6.7	7.7
14	3.9	4.9	5.3	6.4	6.9	7.9
16	3.9	5.0	5.4	6.5	7.0	8.0

Source: Adapted from Palmiter and Kruse (2006).

A derivation of Equation 4 is given in Equation 5 because it is useful for deriving an equation for the thermal resistance of encapsulated ducts in Section 6.2. Assuming a homogenous material with cylindrical geometry, Fourier's law of conduction can be stated as

$$\dot{Q} = -Ak\frac{dT}{dr} \qquad (5)$$

where

A	=	the surface area at radius r (ft^2)
k	=	the conductivity of the material (Btu-in./h-ft^2-°F)
$\dot{Q}$	=	the heat transfer rate (Btu/h)
$\frac{dT}{dr}$	=	the rate of change of temperature with radius (°F/in.).

Since the area of heat flow at radius r is equal to the circumference of the circle $2\pi r$ times the length of the cylinder l, Equation 5 becomes

$$\dot{Q} = 2\pi rlk\frac{dT}{dr}. \qquad (6)$$

The heat flow between any two radii, r_1 and r_2, of a homogenous material can be found by rearranging Equation 6 and integrating from r_1 to r_2.

$$\dot{Q}\int_{r_1}^{r_2}\frac{1}{r}dr = -2\pi lk\int_{T_1}^{T_2}dT \tag{7}$$

Performing the integration and solving for $\dot{Q}$, Equation 7 becomes

$$\dot{Q} = \frac{2\pi lk(T_1 - T_2)}{\ln\left(\frac{r_2}{r_1}\right)}, \tag{8}$$

which is the general form for heat transfer between two radii of a homogenous material with cylindrical geometry.

To apply Equation 8 to the case of round insulated flexible ductwork, let the heat transfer flow from the outer radius r_o to the inner radius r_i. This is equivalent to replacing r_1 to r_o and r_2 with r_i. Recognizing that the definition of thermal resistance of the insulation $R_{insulation}$ is equal to the surface area at radius r_i, multiplied by the temperature difference across the material, and divided by the heat transfer rate

$$R_{insulation} = \frac{2\pi lr_i(T_o - T_i)}{\dot{Q}}, \tag{9}$$

Equation 9 becomes

$$R_{insulation} = \frac{r_i \ln\left(\frac{r_i}{r_o}\right)}{k}. \tag{10}$$

The conductivity k is equal to the nominal thermal resistance divided by the thickness of the material

$$k = \frac{d_o - d_i}{2R_{nominal}}. \tag{11}$$

Replacing the radii terms with diameters and replacing the conductivity term with Equation 11, Equation 10 yields

$$R_{insulation} = \frac{d_i}{d_o - d_i}R_{nominal}\ln\left(\frac{d_i}{d_o}\right), \tag{12}$$

which is Equation 4.

6.2 Encapsulated Ducts

If the ccSPF is installed over existing fiberglass insulation, Equation 3 can be used to calculate the effective R-value of the insulation. Equation 4, however, is not valid because of the different conductivities of the materials. For a ccSPF-encapsulated insulated flexible duct, the heat flows through two concentric cylinders of homogenous insulations with different conductivities (Figure 41).

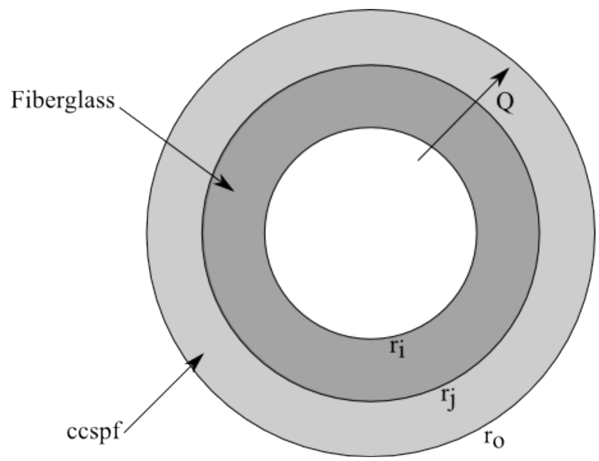


Figure 41. Flexible ductwork encapsulated in ccSPF

Since these materials are homogenous, the heat transfer from r_i to r_j can be found using Equation 8

$$\dot{Q} = \frac{2\pi l k_f \left(T_i - T_j\right)}{\ln\left(\frac{r_j}{r_i}\right)}, \tag{13}$$

where

k_f	=	conductivity of fiberglass (Btu-in./h-ft^2-°F)
r_i	=	inner radius of the duct (in.)
r_j	=	radius of the junction point between the fiberglass and ccSPF (in.)
T_i	=	temperature at r_i (°F)
T_j	=	temperature at r_j (°F).

Similarly, the heat transfer from r_j to r_o is

$$\dot{Q} = \frac{2\pi l k_c \left(T_j - T_o\right)}{\ln\left(\frac{r_o}{r_j}\right)}, \tag{14}$$

where

k_c	=	conductivity of ccSPF (Btu-in./h-ft^2-°F)
r_o	=	outer radius of the duct with insulation (in.)

T_o = temperature at r_o (°F).

Since steady state conduction, the heat transfer from r_i to r_j *is* equal to the heat transfer from r_j to r_o. Therefore, the heat transfer terms in Equations 13 and 14 are equivalent. Since the actual R-value of the duct is equal to

$$R_{insulation} = \frac{A_i\left(T_i - T_o\right)}{\dot{Q}}, \tag{15}$$

where A_i is the area of the duct at r_i. $R_{insulation}$ can be found by solving Equations 13 and 14 for the right-hand term of Equation 15. By solving Equation 14 for T_j

$$T_j = \frac{\dot{Q}\ln\left(\frac{r_o}{r_j}\right)}{2\pi l k_c} + T_o, \tag{16}$$

replacing T_j in Equation 13 with the right-hand term of Equation 16

$$\dot{Q}k_c \ln\left(\frac{r_j}{r_i}\right) = 2\pi l k_f k_c\left(T_i - T_o\right) - k_f \dot{Q}\ln\left(\frac{r_o}{r_j}\right), \tag{17}$$

and grouping like terms, Equation 17 becomes

$$\dot{Q}\left[k_c \ln\left(\frac{r_j}{r_i}\right) + k_f \ln\left(\frac{r_o}{r_j}\right)\right] = 2\pi l k_f k_c\left(T_i - T_o\right). \tag{18}$$

Since the area of the duct at the inner radius A_i is equal to

$$A_i = 2\pi r_i l, \tag{19}$$

$2\pi l$ in Equation 18 can be replaced with A_i/r_i

$$\dot{Q}r_i\left[k_c \ln\left(\frac{r_j}{r_i}\right) + k_f \ln\left(\frac{r_o}{r_j}\right)\right] = A_i k_f k_c\left(T_i - T_o\right). \tag{20}$$

Rearranging Equation 20 to solve for the right-hand term of Equation 15

$$\frac{A_i\left(T_i - T_o\right)}{\dot{Q}} = \frac{r_i\left[k_c \ln\left(\frac{r_j}{r_i}\right) + k_f \ln\left(\frac{r_o}{r_j}\right)\right]}{k_f k_c}, \tag{21}$$

and replacing the left-hand term for $R_{insulation}$, the equation for $R_{insulation}$ as a function of the conductivities and radii of the materials is

$$R_{insulation} = \frac{r_i\left[k_c \ln\left(\frac{r_j}{r_i}\right) + k_f \ln\left(\frac{r_o}{r_j}\right)\right]}{k_f k_c}. \tag{22}$$

To write Equation 22 in terms of the R-values of the insulations, the conductivity of fiberglass can be replaced with

$$k_f = \frac{r_j - r_i}{R_{f,nominal}}, \tag{23}$$

and the conductivity of ccSPF can be replaced with

$$k_c = \frac{r_o - r_j}{R_{c,nominal}}, \tag{24}$$

where $R_{f,nominal}$, and $R_{c,nominal}$ represent the nominal R-values of the insulation application typically reported. Rewriting Equation 22 in terms of the nominal R-values yields

$$R_{insulation} = r_i\left[\frac{R_{f,nominal}}{r_j - r_i}\ln\left(\frac{r_j}{r_i}\right) + \frac{R_{c,nominal}}{r_o - r_j}\ln\left(\frac{r_o}{r_j}\right)\right]. \tag{25}$$

Table 9 lists results for R-4.2, R-6, and R-8 round insulated ductwork encapsulated in 1- to 2.5-in of ccSPF. R-values in this table are given in h-ft^2-°F/Btu, where the surface area is based on the inner diameter of the duct. These results assume the same internal and external film resistances and fiberglass R-value (3.36/in.) from the previous section. The results also assume that closed-cell spray foam has an R-value of R-6.7/in.

Table 9. Effective R-Values of ccSPF Encapsulated Round Flexible Ducts by Insulation Thickness

	R-4.2 Flex Duct				R-6.0 Flex Duct				R-8.0 Flex Duct			
ccSPF Thickness (in.)	1	1.5	2	2.5	1	1.5	2	2.5	1	1.5	2	2.5
Nominal R-Value	10.9	14.3	17.6	21.0	12.7	16.1	19.4	22.8	14.7	18.1	21.4	24.8
4-in. Diameter	7.6	9.0	10.4	11.6	8.1	9.4	10.6	11.7	8.7	9.9	10.9	11.9
6-in. Diameter	8.6	10.4	12.0	13.6	9.3	11.0	12.5	13.9	10.1	11.6	13.0	14.3
8-in. Diameter	9.2	11.3	13.1	14.9	10.1	12.0	13.7	15.4	11.0	12.7	14.4	15.9
10-in. Diameter	9.7	11.9	13.9	15.9	10.6	12.7	14.7	16.5	11.7	13.6	15.4	17.1
12-in. Diameter	10.0	12.3	14.5	16.6	11.1	13.3	15.4	17.3	12.2	14.3	16.2	18.1
14-in. Diameter	10.2	12.7	15.0	17.2	11.4	13.7	15.9	18.0	12.6	14.8	16.9	18.9
16-in. Diameter	10.4	13.0	15.4	17.7	11.6	14.1	16.4	18.6	12.9	15.2	17.4	19.5

6.3 Buried Ducts

Unlike insulated and encapsulated round ductwork, the thermal resistance of buried ducts cannot be found analytically. Instead, a finite-element heat transfer model must be used to determine the effective R-value of buried ductwork. For this analysis, THERM 6.3, which is a two-dimensional heat-transfer modeling program developed by the Lawrence Berkeley National Laboratory (LBNL), was used to calculate effective and apparent R-values. A diagram of the buried duct modeling configuration is shown in Figure 42.

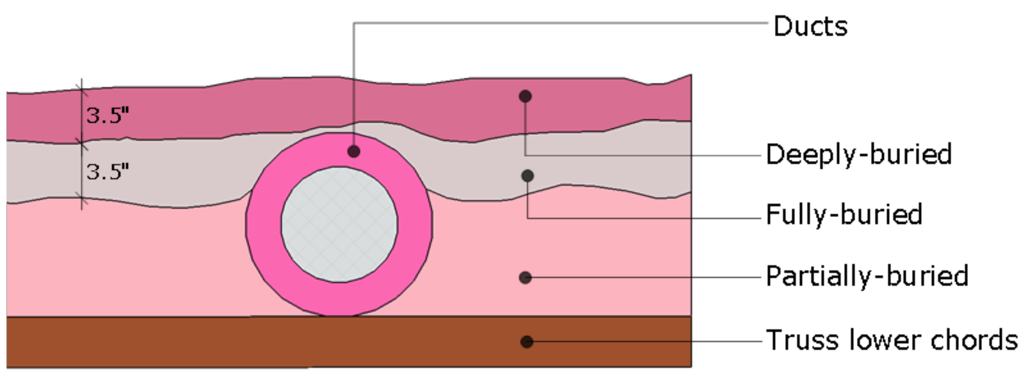


Figure 42. Diagram of buried duct modeling configuration

The conductivities and thicknesses of the materials used in this model (see Figure 43 for diagram of buried duct configuration) are shown in Table 10. All emissivities were set to 0.9, which is the default for all materials in the THERM library. Simulations were ended with a heat transfer error less than 3%.

Table 10. Material Conductivities and Thicknesses

Material	Conductivity *k* (Btu-in./h-ft^2-°F)	Thickness (in.)
Loose-Fill Fiberglass	0.4	Depends on configuration (see Figure 5 for depth of burial classes)
Insulating Duct Wrap	0.298	Depends on duct insulation
16-in. on Center Joists With Loose-Fill Fiberglass Insulation (Weighted Average of Framing and Insulation)	0.464	3.5
Gypsum Board	1.1	0.5

Table 11 gives boundary conditions, which include temperature and surface film resistance, for all surfaces. The film resistances for the different duct diameters are taken from Palmiter and Kruse (2006), and the attic and conditioned space film resistances are identical to those found in previous studies (CARB 2003; Griffiths and Zuluaga 2004), on buried ducts. Boundary conditions were implemented using THERM's simplified convection/linearized radiation model.

Table 11. Boundary Conditions

Boundary condition	Temperature (°F)	Surface film resistance (Btu/h-ft^2-°F)
Conditioned Space	75	1.76
Attic Air	120	1.76
4-in. Duct Interior	55	2.22
6-in. Duct Interior	55	2.04
8-in. Duct Interior	55	1.92
10-in. Duct Interior	55	1.85
12-in. Duct Interior	55	1.79
14-in. Duct Interior	55	1.72
16-in. Duct Interior	55	1.69

Apparent and effective R-values for buried round ductwork are shown in Table 12 and Table 13, respectively. Effective R-values for R-4.2 ducts are similar to those calculated by Griffiths and Zuluaga (2004). Differences between these numbers might be attributable to different simulation programs and the error levels of the simulation. Apparent R-values are similar to effective R-values for smaller, partially buried ducts, but become significantly smaller for larger, deeply buried ducts.

Table 12. Effective R-Values of Buried Round Ducts

	R-4.2 Ducts			R-6 Ducts			R-8 Ducts		
Burial Level	**Partially**	**Fully**	**Deeply**	**Partially**	**Fully**	**Deeply**	**Partially**	**Fully**	**Deeply**
4-in. Diameter	5.6	8.4	14.3	7.1	9.9	15.2	8.5	11.2	16.1
6-in. Diameter	6.9	10.4	17.8	8.7	12.2	19.0	9.3	13.9	20.1
8-in. Diameter	8.1	12.0	20.7	10.2	14.1	22.1	12.3	16.2	23.5
10-in. Diameter	9.0	13.4	23.1	11.4	15.8	24.7	13.7	18.1	26.3
12-in. Diameter	9.9	14.7	25.2	12.5	17.2	27.0	15.0	19.7	28.8
14-in. Diameter	10.7	15.8	27.1	13.4	18.5	29.0	16.2	21.2	31.1
16-in. Diameter	11.5	16.8	28.9	14.3	19.8	31.0	17.3	22.6	33.1

Table 13. Apparent R-Values of Buried Round Ducts

	R-4.2 Ducts			R-6 Ducts			R-8 Ducts		
Burial Level	**Partially**	**Fully**	**Deeply**	**Partially**	**Fully**	**Deeply**	**Partially**	**Fully**	**Deeply**
4-in. Diameter	5.6	8.3	13.3	7.1	9.7	14.3	8.5	11.0	15.3
6-in. Diameter	6.8	9.9	16.0	8.6	11.7	17.3	9.3	13.3	18.4
8-in. Diameter	7.8	11.3	18.1	9.9	13.2	19.6	11.8	15.1	21.0
10-in. Diameter	8.7	12.4	19.9	10.9	14.6	21.5	13.0	16.7	23.1
12-in. Diameter	9.4	13.4	13.4	11.8	15.7	23.2	14.1	18.0	24.9
14-in. Diameter	10.1	14.3	22.8	12.6	16.7	24.7	15.1	19.2	26.6
16-in. Diameter	10.7	15.1	24.1	13.3	17.8	26.1	16.0	20.3	28.1

6.4 Buried and Encapsulated Ducts

Effective and apparent R-values of buried and encapsulated ducts were similarly calculated using THERM. All boundary materials and conductivities were identical to the previous simulations, and the ccSPF insulation had a conductivity of 0.149 Btu-in./h-ft^2-°F and a thickness of 1.5 in. Figure 43 is a diagram of the buried and encapsulated duct configuration used in the modeling. Effective and apparent R-values for buried and encapsulated ducts are shown in Table 14 and Table 15, respectively. Partially, fully, and deeply buried ducts are defined in the same manner as in previous research, as shown in Figure 5 (Griffiths and Zuluaga 2004; Griffiths et al. 2004; Griffiths et al. 2002).

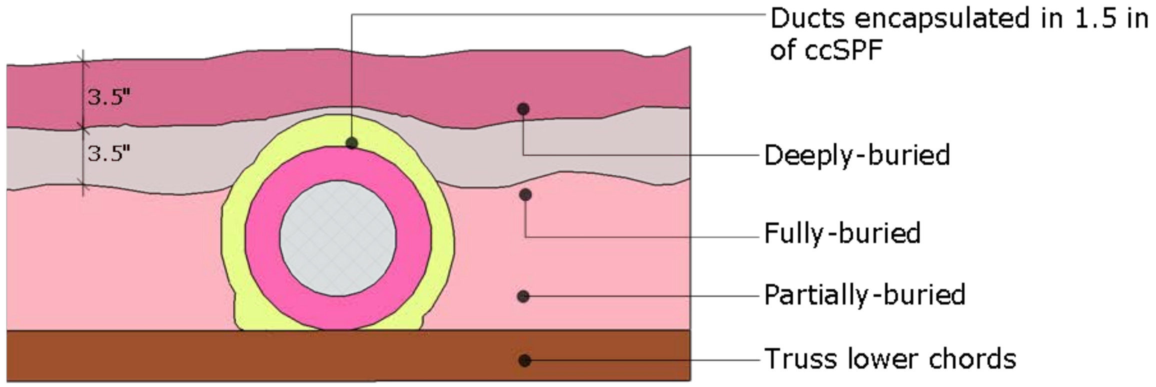


Figure 43. Diagram of buried and encapsulated ducts

As previously mentioned, the differences between the apparent and effective R-values are caused by heat transfer between the air inside the duct and the interior building air. As suggested by the relatively small differences between effective and apparent R-values, the vast majority of the heat transferred to the duct comes from the attic at design conditions, as shown in Figure 44. The color gradient in Figure 44 indicates magnitude, not direction. The area directly under the duct shows heat flux from the interior space to the duct. The areas to the far right and left of the duct show heat flux from the attic to the interior space, and the areas in between have small heat magnitudes as the heat flux direction changes.

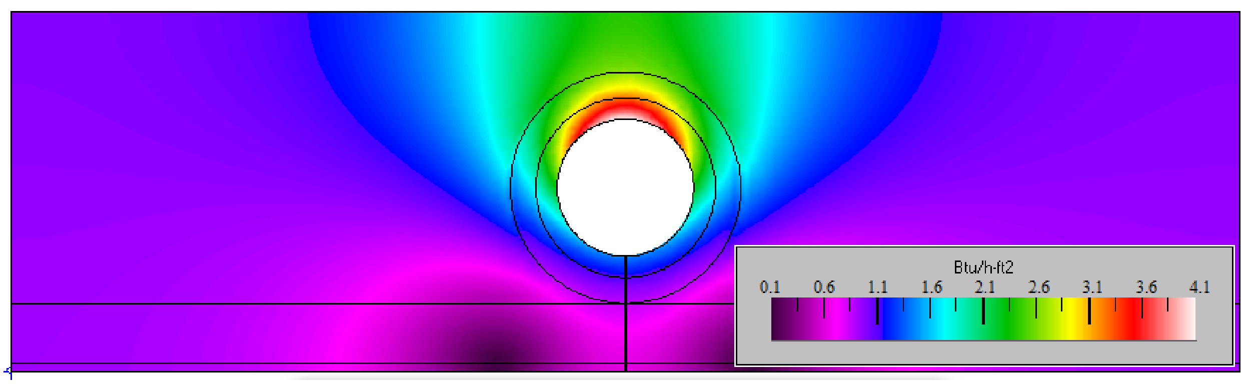


Figure 44. Heat flux magnitude through encapsulated and fully buried 8-in. diameter duct

Table 14. Effective R-Values of Buried and Encapsulated Round Ducts

	R-4.2 Ducts			R-6 Ducts			R-8 Ducts		
Burial Level	**Partially**	**Fully**	**Deeply**	**Partially**	**Fully**	**Deeply**	**Partially**	**Fully**	**Deeply**
4-in. Diameter	12.8	15.7	20.4	13.6	16.3	20.7	14.4	17.0	21.1
6-in. Diameter	15.8	19.5	25.5	16.9	20.4	26.0	18.0	21.5	26.6
8-in. Diameter	18.4	22.6	29.6	19.7	23.8	30.3	21.0	25.0	31.1
10-in. Diameter	20.6	25.3	33.0	22.0	26.6	34.0	23.6	28.0	35.0
12-in. Diameter	22.5	27.5	36.0	24.1	29.0	37.1	25.8	30.6	38.3
14-in. Diameter	24.2	29.5	38.7	26.0	31.3	39.9	27.9	33.0	41.3
16-in. Diameter	25.8	31.4	41.1	27.7	33.2	42.5	29.7	35.2	44.0

Table 15. Apparent R-Values of Buried and Encapsulated Round Ducts

	R-4.2 Ducts			R-6 Ducts			R-8 Ducts		
Burial Level	**Partially**	**Fully**	**Deeply**	**Partially**	**Fully**	**Deeply**	**Partially**	**Fully**	**Deeply**
4-in. Diameter	12.8	15.6	19.7	13.6	16.2	20.1	14.4	16.8	20.4
6-in. Diameter	15.7	18.9	23.9	16.7	19.8	24.5	17.7	20.8	25.1
8-in. Diameter	17.8	21.4	27.1	19.1	22.5	27.9	20.3	23.6	28.7
10-in. Diameter	19.7	23.5	29.7	21.0	24.8	30.7	22.5	26.1	31.7
12-in. Diameter	21.2	25.3	31.9	22.7	26.7	33.0	24.3	28.2	34.2
14-in. Diameter	22.6	26.9	33.9	24.3	28.5	35.2	26.0	30.1	36.5
16-in. Diameter	23.8	28.3	35.6	25.7	30.0	37.0	27.5	31.8	38.5

Since the ductwork of the homes tested in this report were buried under a mound of loose-fill insulation, not buried under a plane of insulation, effective and apparent R-values of encapsulated ducts buried under a mound of insulation were also computed. Mounded-buried ducts are defined for the purpose of modeling as bounded by an arc that peaks 1 in. above the duct and meets the line tangent to the bottom with a distance of three times the duct's outer diameter, $3d_o$, between the edges of the fiberglass (Figure 45).

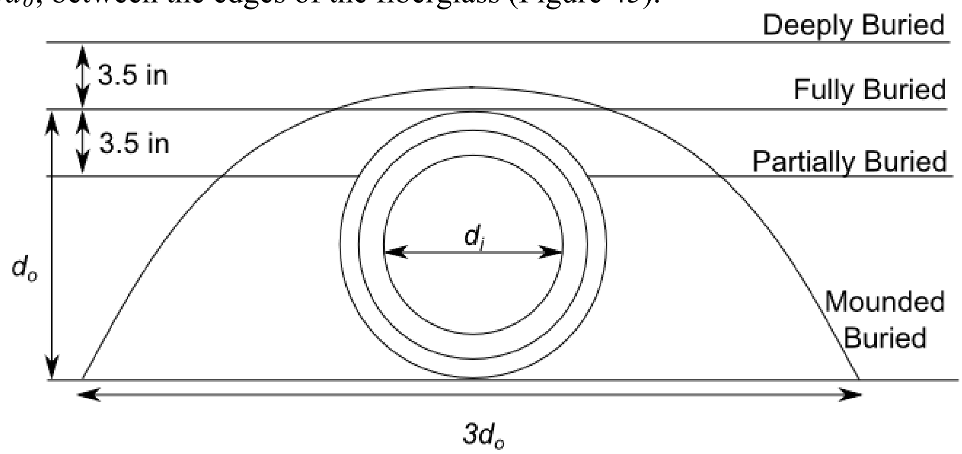


Figure 45. Definition of mounded-buried ducts

Table 16 contains effective and apparent R-values for mounded-buried encapsulated ducts. These R-values are surprisingly similar to fully buried encapsulated duct R-values. The slight reduction in R-value for mounded ducts is attributable to the increased heat transfer through the sides of the duct. A large amount of this heat transfer increase is offset by an increase in the amount of insulation above the duct (1 in. of insulation was assumed to cover the top of the duct for the mounded case, and no insulation was assumed for the fully buried case).

Table 16. R-Values of Mounded-Buried R-4.2 Ducts Encapsulated in 1.5 in. of ccSPF

Duct Inner Diameter (in.)	$R_{effective}$	$R_{apparent}$
4	15.2	15.2
6	18.7	18.5
8	21.6	20.9
10	24.1	22.9
12	26.2	24.6
14	28.1	26.2
16	29.8	27.5

R-values of buried and encapsulated ducts increase dramatically with increased inner diameter (Figure 46). The direct relationship between effective R-value and duct diameter could be caused by two properties of the insulation geometry. First, increasing the duct size also increases the total depth of the fiberglass insulation, which reduces the heat transfer from the bottom of the duct toward the attic. Second, just as the R-values of traditionally insulated ducts change with duct inner diameter because of the cylindrical geometry of round ductwork, the R-values of buried and encapsulated round ductwork will be affected by inner diameter. Since the impact of inner diameter is greater for buried and encapsulated ducts than for traditionally insulated round ductwork, the increased R-values are likely caused by a combination of these factors.

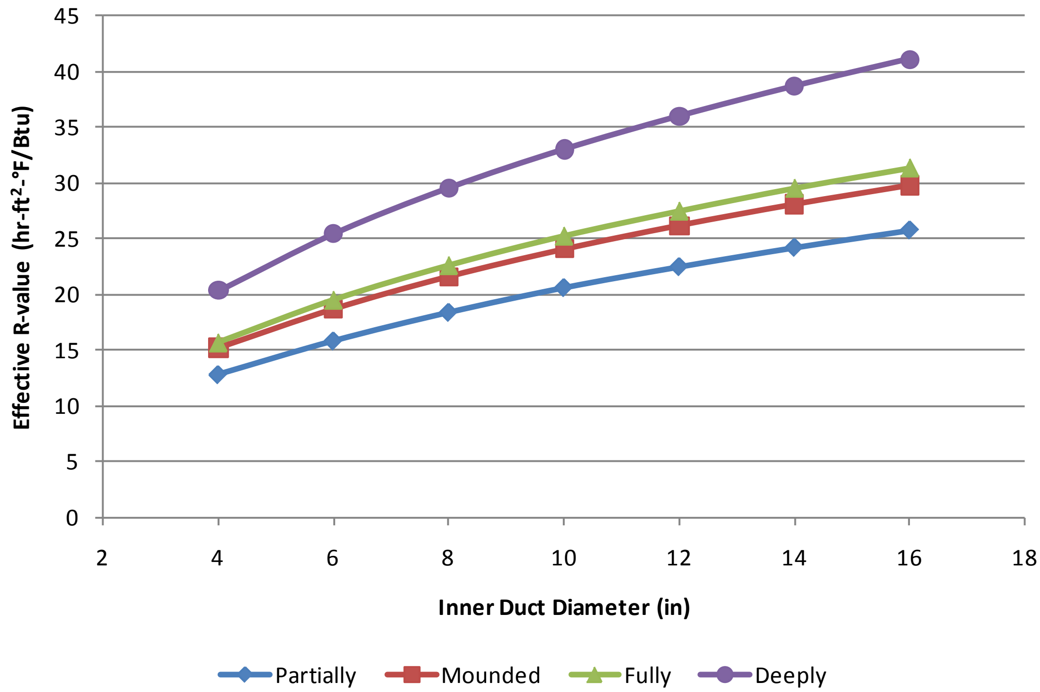


Figure 46. Effective R-values of R-4.2 buried and encapsulated ducts

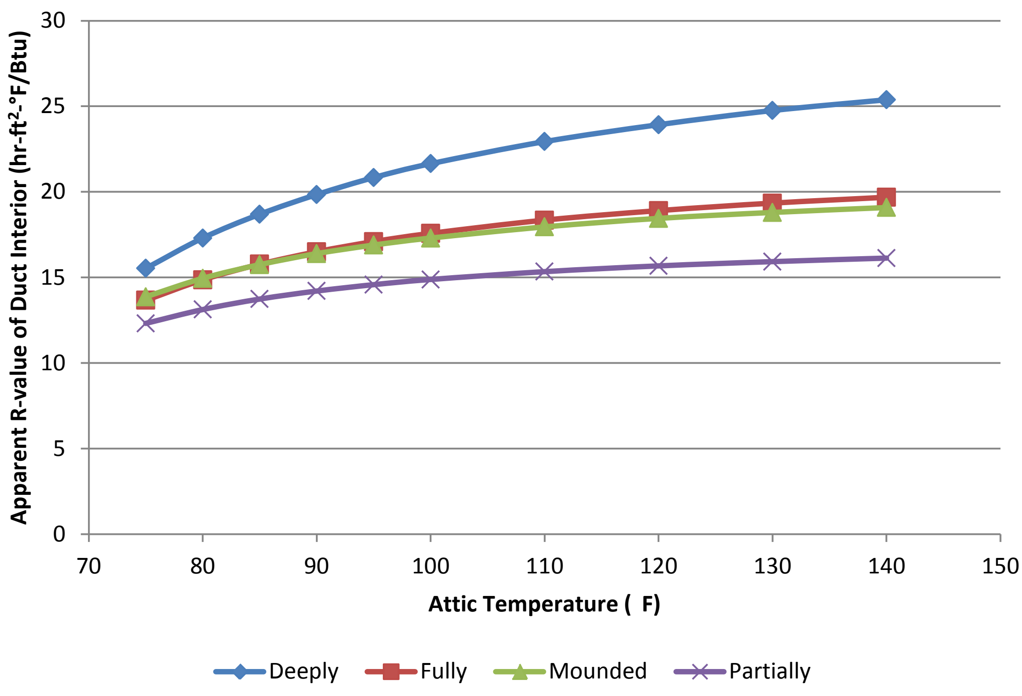


Figure 47. Apparent R-values of 6-in. buried ducts encapsulated in ccSPF by attic temperature

Finite-element modeling showed that effective R-values are independent of boundary condition temperatures, but apparent R-values are highly dependent on boundary condition temperature.

The large insulation levels, coupled with the location of the ducts in relation to the interior space, mean that heat gains or losses are dependent on both the interior temperature and the attic temperature. As a result, changes in the attic temperature, duct interior temperature, or interior temperature will result in a change in the heat flow through the cross-section and a change in apparent R-value. Figure 47 shows the effect of attic temperature on the R-value of a 6-in. buried and encapsulated duct. The temperature change causes a large change in apparent R-value, particularly for deeply buried ducts. In this case, the apparent R-value dropped by almost 40% when the temperature changed from 120°F to 75°F. Table 17 summarizes effective R-values of an 8-in. duct by insulation strategy.

Table 17. Summary of Duct Effective R-Values for 8-in. Duct by Insulation Strategy

Duct Configuration	R-4.2 Ducts	R-6 Ducts	R-8 Ducts
Traditional Hung Ducts	4.6	5.9	7.2
Hung Ducts Encapsulated in 1.5 in. of ccSPF	11.3	12.0	12.7
Partially Buried	8.1	10.2	12.3
Fully Buried	12.0	14.1	16.2
Deeply Buried	20.7	22.1	23.5
Encapsulated in 1.5 in. of ccSPF and Partially Buried	18.4	19.7	21.0
Encapsulated in 1.5 in. of ccSPF and Fully Buried	22.6	23.8	25.0
Encapsulated in 1.5 in. of ccSPF and Deeply Buried	29.6	30.3	31.1

7 Effective Heat Transfer Coefficients of Test Home Ductwork and R-Value Validation

Using the R-values calculated in Section 6, the overall effective and apparent UA values of the ductwork in the three Jacksonville houses were calculated and are shown in Table 18. For plenum boxes used to connect trunks and branches together, the R-value cannot be modeled in THERM because of the three-dimensional nature of the geometry. Instead, these boxes were assigned an R-value equal to the R-value of a round duct of a similar size. Although not exact, this method should give an approximate result for these boxes. For House 2, which has rectangular ductwork, each of the duct sizes were modeled in THERM. The existing configuration was already partially buried as a result of the configuration of the ductwork and the fiberglass blown-in insulation (see Figure 8 and Figure 10). The fiberglass insulation was assumed to be installed at a level 3 in. above the bottom of the duct. Post-retrofit ducts were assumed to have mounded burial with a configuration similar to that shown in Figure 45, and the dimension d_o equals the outer width of the duct parallel to the ceiling.

Table 18. Theoretical UA Values for Monitored Jacksonville Houses

	Pre-Retrofit			Post-Retrofit			Reduction in Apparent UA (%)	Reduction in Effective UA (%)
	Area (ft^2)	Apparent UA (Btu/h-°F)	Effective UA (Btu/h-°F)	Area (ft^2)	Apparent UA (Btu/h-°F)	Effective UA (Btu/h-°F)		
House 1	339.3	72.1	72.1	374.4	17.4	17.1	75.9	76.3
House 2	546.1	91.9	90.3	563.1	24.5	21.6	73.3	76.1
House 3	214.4	46.2	46.2	214.4	19.3	19.3	58.2	58.2

The values shown in Table 18 can be validated using test data collected during field monitoring. When the space-conditioning system is running in steady-state operation, the heat transfer between the conditioned air inside the duct and the attic temperature can be simplified as a heat exchanger. Using this simplification, the heat transfer between the duct and the attic is governed by

$$UA = \frac{\dot{Q}}{LMTD} \qquad (26)$$

where

$\dot{Q}$ = the heat transfer rate between the duct and attic (Btu/h), as defined by Equation 28

U = the heat transfer coefficient (Btu/h-ft^2-°F)

A = interior surface area of duct (ft^2), and

$LMTD$ = log mean temperature difference (°F), as defined by Equation 27.

The *LMTD* is the logarithmic mean between two ends, *A* and *B*, of a heat exchanger.

$$LMTD = \frac{\Delta T_A - \Delta T_B}{\ln \dfrac{\Delta T_A}{\Delta T_B}} \tag{27}$$

In this application, stream *A* is the supply temperature of the duct, where

$$\Delta T_A = T_{supply} - T_{attic},$$

and stream *B* is the discharge temperature, where

$$\Delta T_B = T_{discharge} - T_{attic}.$$

The heat transfer rate is

$$\dot{Q} = 1.08 \times \dot{V} \times \left(T_{supply} - T_{discharge}\right), \tag{28}$$

where $\dot{V}$ is the volumetric flow rate (ft^3/min).

For typical trunk and branch distribution systems, however, the overall heat transfer coefficient of the system will not equal the sum of each discharge because multiple discharges will share the same branch. Instead, each heat transfer rate and *LMTD* must be calculated independently. The *LMTD*s must be weighted as a fraction of the total airflow. The overall UA is the ratio of the summed heat transfer rates and weight *LMTD*s. This equation is defined as

$$UA = \frac{\sum \dot{Q}_i}{\sum w_i LMTD_i}, \tag{29}$$

where *i* represents the index of the discharge register and w_i is the airflow fraction $\dot{V}_i / \dot{V}$ for discharge *i*.

To ensure that these calculations are valid, periods of operation that appear to be largely steady state were isolated from the monitored data. Since apparent R-values vary with temperature, periods with attic temperature near 120°F, which is the boundary condition used in the finite element modeling, were used. The entire UA of the system cannot be effectively calculated because only four duct discharge temperatures were measured. Instead, the percent change in UA after the retrofit can be calculated from the relative apparent UAs calculated using the method described previously.

Table 19 lists mean apparent UA values and standard deviations from the steady-state period identified in the data. The removal of the large hole in the ductwork at House 2 led to changes in the airflows of this system, which resulted in difficulties in measuring UA. The post-retrofit UAs for House 2 were significantly higher than the pre-retrofit UAs and the House 2 data was deemed useless for this analysis.

Table 19. Relative Apparent UAs as Measured in Test Houses

House	Pre-Retrofit					Post-Retrofit					Reduction in Apparent UA (%)
	N	Apparent UA		T_{attic}		N	Apparent UA		T_{attic}		
		Mean	Std.	Mean	Std.		Mean	Std.	Mean	Std.	
1	8	13.4	0.6	120.8	4.0	3	2.51	0.72	120.7	5.4	81.3
3	6	34.1	0.01	120.6	2.4	4	11.2	0.4	121.3	3.7	67.2

The apparent UA reductions listed in Table 18 and Table 19 are relatively close, with UA reductions varying by no more than 10%. Given that the UAs calculated theoretically cannot account for plenum boxes and the issues with measuring apparent UA using a method that assumes steady-state operation, the team concluded that these values reflect a reasonable level of agreement.

8 ASHRAE 152 Distribution System Efficiencies

The heat transfer coefficients calculated in Sections 6 and 7 are necessary for calculating the efficiency of the thermal distribution systems. The efficiency of thermal distribution systems can be estimated using ASHRAE Standard 152, which determines "the efficiency of space heating and/or cooling thermal distribution systems under seasonal and design conditions" (ASHRAE 2004; 2). Standard 152 provides a methodology for calculating the delivery effectiveness (DE) and distribution system efficiency (DSE) of a thermal distribution system.

The DE is defined as "the ratio of the thermal energy transferred to or from the conditioned space to the thermal energy transferred at the equipment distribution system heat exchanger" (ASHRAE 2004; 2). The DSE includes losses calculated in the DE and adds losses associated with the impact of unbalanced leakage on building infiltration, energy recovery from losses to buffer zones, and losses associated with space-conditioning system cycling. The DSE is

$$DSE = DE_{corr} F_{equip} F_{load} \left(1 - F_{cycloss}\right), \quad (30)$$

where

F_{equip}	=	equipment factor
F_{load}	=	infiltration factor
$F_{cycloss}$	=	equipment cycling factor
DE_{corr}	=	DEs corrected for regain.

All DE and DSE calculations were performed in compliance with ASHRAE Standard 152-2004, except where explicitly noted. A spreadsheet developed by LBNL in this analysis (LBNL 2003). To calculate the corrected DE, regain factors for supply and return ducts are needed. Airflow between the attic and conditioned space was not measured, so these values cannot be calculated explicitly. Instead, the default regain factors of 0.1 used in LBNL's ASHRAE 152 spreadsheet were used in this analysis.

Calculation of the infiltration factor requires effective leakage area L_n. Blower door tests were performed at 50 Pa, and L_n was calculated using an approximately equivalent expression for single-story homes (Sherman 1986), which is shown in Equation 31. See ASTM (1987), ASHRAE (1993), and ASHRAE (1998) for detailed information about calculating L_n exactly.

$$L_n \approx \frac{ACH_{50}}{20} \quad (31)$$

Input values used in the ASHRAE 152 calculation are taken from Table 4 and Table 5. ASHRAE 152 DEs, corrected DEs, and DSEs are summarized in Table 20 through Table 22. As the summary tables show, the retrofit resulted in a dramatic increase, typically 12% or greater, in DE in all three homes. Similarly, the retrofit resulted in DSE increases. The cooling seasonal DSE increased by 11% in House 1, by 25% in House 2, and by 10% in House 3.

The similar DE improvements in House 1, in which the ducts were encapsulated and buried, and House 3, in which the ducts were only encapsulated, could be explained by several factors. First, the improvements in duct leakage will have a larger impact in R-value because duct leakage has a one-to-one direct relationship with duct losses. Second, the ductwork was lengthened in House 1, which will reduce the impact of the R-value increase. The remaining DE improvements are associated with the increased R-value.

Table 20. Pre- and Post-Retrofit ASHRAE 152 DE and DSEs for House 1

	Pre-Retrofit			Post-Retrofit		
	DE (%)	Corrected DE (%)	DSE (%)	DE (%)	Corrected DE (%)	DSE (%)
Heating Design	83	85	84	96	96	98
Heating Seasonal	84	86	85	96	97	97
Cooling Design	80	82	82	95	96	97
Cooling Seasonal	85	86	86	97	97	97

Table 21. Pre- and Post-Retrofit ASHRAE 152 DE and DSEs for House 2

	Pre-Retrofit			Post-Retrofit		
	DE (%)	Corrected DE (%)	DSE (%)	DE (%)	Corrected DE (%)	DSE (%)
Heating Design	61	64	58	84	85	84
Heating Seasonal	66	69	65	86	87	86
Cooling Design	43	47	39	77	78	73
Cooling Seasonal	59	62	54	83	84	79

Table 22. Pre- and Post-Retrofit ASHRAE 152 DE and DSEs for House 3

	Pre-Retrofit			Post-Retrofit		
	DE (%)	Corrected DE (%)	DSE (%)	DE (%)	Corrected DE (%)	DSE (%)
Heating Design	84	85	85	95	95	95
Heating Seasonal	85	86	85	95	96	95
Cooling Design	82	84	79	94	94	90
Cooling Seasonal	86	87	81	95	96	91

9 Condensation Potential of Encapsulated and Buried Ducts

As noted in Section 5.3, condensation will occur on the surface of the duct if the surface temperature is below the dew point of the surrounding air. Although the attic air temperature and relative humidity were monitored during the field testing, the dew point of the air surrounding specific points on the duct profile cannot be determined because of the complex process of vapor transport. The steady-state, two-dimensional, thermal modeling outlined in previous sections was combined with one-dimensional, dynamic, hygrothermal modeling to predict the potential for condensation on the surface of the duct.

The hygrothermal modeling program WUFI Pro 5 was used to simulate the movement of water vapor through the attic assembly. The hygrothermal modeling was used to determine the dew point of the air through the depth of the attic insulation assembly. These dew points were then compared to the surface temperatures of the duct at each depth, as calculated using two-dimensional steady-state modeling.

This analysis was conducted for buried ducts and buried and encapsulated ducts using the worst case of the modeling configurations described previously, a 4-in. R-4.2 duct deeply buried beneath attic insulation. Attic temperatures and relative humidities from one of the houses monitored in the research were used to simulate the conditions of an attic in a hot-humid climate. A constant temperature of 75°F and a relative humidity of 50% were applied to the interior conditions. The supply duct air was not explicitly modeled because of the geometric limitations of WUFI Pro 5. The maximum dew points along the depth of the duct corresponded to the highest attic temperatures monitored in this study. The resulting air dew points were compared to the steady-state surface temperatures predicted by THERM for the boundary attic condition of 130°F.

The results from the analysis (Figure 48) predict condensation issues for the buried ducts without additional ccSPF insulation, which was observed by Griffiths et al. (2002). Figure 48 shows the potential for condensation across the entire surface area of the duct under these conditions. The surface temperature of the duct, marked as black isotherms, is lower than the dew point of the surrounding air, which is marked in red. This case is more severe than the conditions observed by Griffiths et al. (2002) because it ignores the effects of leakage from the interior and the duct. As a result, this case can be viewed as the worst case potential for condensation.

A similar analysis of a buried and encapsulated duct shows no potential for condensation (Figure 49). The surface temperature is lower than the dew point of the air across the entire depth of the insulation. These results validate that the potential for condensation can be mitigated by encapsulating buried ducts in a layer of 1.5-in. ccSPF insulation. The closeness of duct surface temperature and the dew point of the surrounding air at the bottom of the duct emphasizes that 1.5 in. of ccSPF should be the minimum insulation level applied to R-4.2 ducts. For ductwork with higher existing R-values, lower ccSPF thicknesses might be possible, although consistently applying lower thicknesses might not be possible.

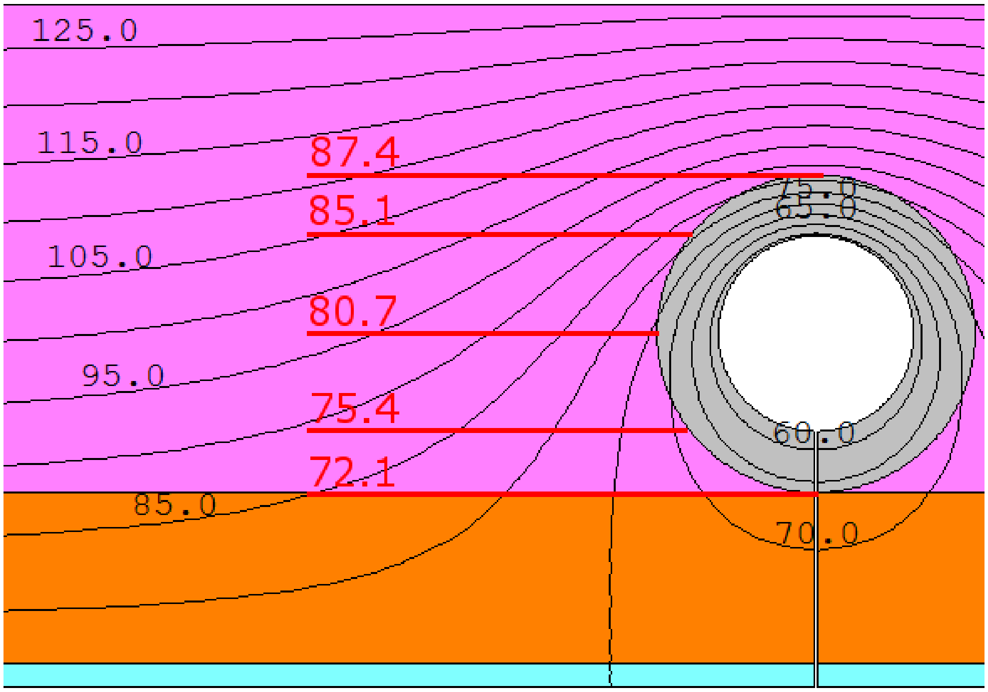


Figure 48. R-4.2 duct (4 in.) deeply buried in fiberglass insulation. Isotherms from the steady state model (in black) are compared to the dew point of the air at several key locations (in red).

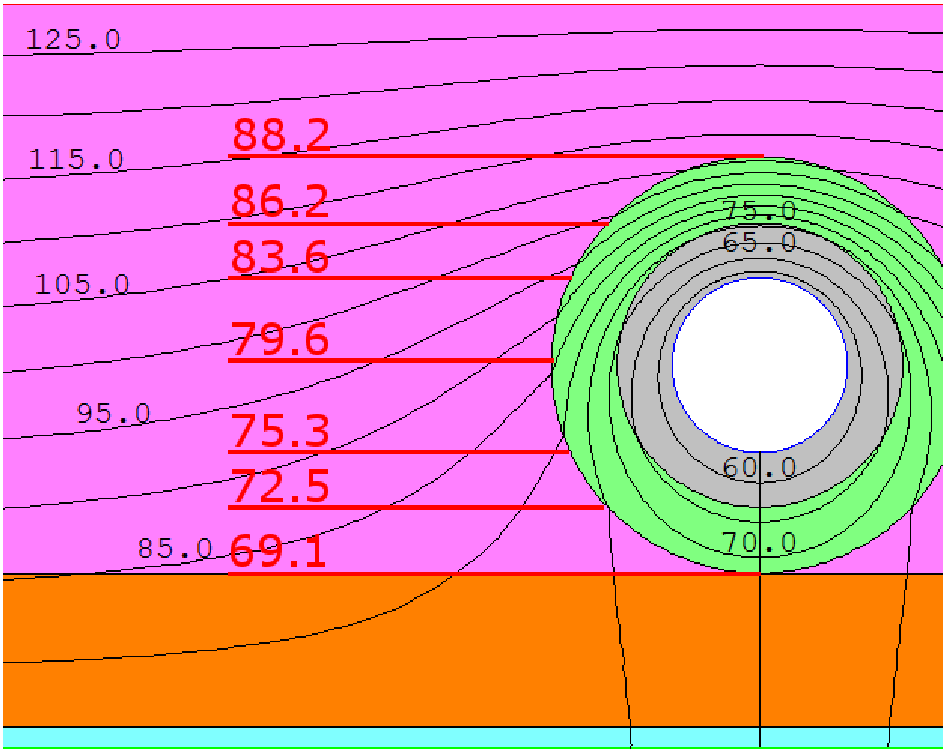


Figure 49. R-4.2 duct (4 in.) deeply buried in fiberglass insulation and encapsulated in 1.5 in. of ccSPF. Isotherms from the steady-state model (in black) are compared to the dew point of the air at several key locations (in red).

10 Predicted Energy and Cost Savings

Energy savings were predicted in Building Energy Optimization (BEopt)E+ 1.2 using the specifications given in Table 4 and Table 5. The pre-retrofit BEopt models were calibrated using utility bill data collected for 20 months before the start of the retrofit. Heating and cooling set-point temperatures and miscellaneous electric load multipliers were modified to match the observed utility bills. A utility bill analysis was used to match modeled and observed utility bills and account for differences between the observed temperatures and the typical meteorological year. The utility analysis was performed using a multivariate, linear, least-squares regression of the form

$$E = \beta_1 N_{days} + \beta_2 CDD_{75} + \beta_3 HDD_{65}, \quad (32)$$

where

E	=	electricity use during the billing period (kWh)
N_{days}	=	number of days in the billing period
CDD_{75}	=	cooling degree days at base 75°F
HDD_{65}	=	heating degree days at base 65°F
β_1, β_2, and β_2	=	regression coefficients.

This methodology is similar to that used by the PRISM model, but employs a fixed base for the CDD and HDD calculations (Fels 1986). Table 23 shows the regression statistics—including the coefficient value, t-statistic, and p-value—for the pre-retrofit utility bills collected for 20 months before the retrofits began. The resulting regression coefficients were statistically significant at the 95% confidence level. At House 3, the initial regression found a negative coefficient for the HDD variable that was statistically insignificant at the 95% confidence level. The resulting coefficient was thus forced to zero and ignored in this analysis.

Table 23. Regression Statistics for Pre-Retrofit Utility Bills

	House 1 $R^2 = 0.974$ N = 20, dof[a] = 17			House 2 $R^2 = 0.985$ N = 20, dof = 17			House 3 $R^2 = 0.989$ N = 20, dof = 18		
	coef.	t	p	coef.	t	p	coef.	t	p
N_{days}	16.3	5.15	7.97×10^{-5}	50.8	11.8	1.28×10^{-9}	54.25	30.0	8.14×10^{-5}
CDD_{75}	4.02	4.95	1.21×10^{-4}	7.40	6.86	2.77×10^{-6}	4.52	7.34	8.12×10^{-5}
HDD_{65}	2.56	8.91	8.20×10^{-8}	1.06	2.70	1.54×10^{-2}	N/A	N/A	N/A

[a]Degrees of freedom

Table 24 shows identical statistics for the weather data used in and the energy predictions by BEopt. The coefficients are all statistically significant at the 95% confidence level and match the coefficients in Table 23 far better than typical energy models. Because these retrofits were completed relatively recently, insufficient data are available to use utility bill analysis to compare pre- and post-retrofit energy savings. To visualize these results, the resulting pre-retrofit predicted utility bills are compared in Figure 50 to a 1-year period as observed at the Jacksonville houses.

Table 24. Regression Statistics for Pre-Retrofit Energy Predictions (BEoptE+ 1.2)

	House 1 $R^2 = 0.999$ N = 12, dof = 9			House 2 $R^2 = 0.999$ N = 12, dof = 9			House 3 $R^2 = 0.997$ N = 12, dof = 10		
	coef.	t	p	coef.	t	p	coef.	t	p
N_{days}	25.0	24.7	1.38×10^{-9}	52.5	25.9	9.34×10^{-10}	49.8	39.7	2.43×10^{-12}
CDD_{75}	2.79	11.5	1.11×10^{-6}	8.11	16.6	4.61×10^{-8}	4.41	11.5	4.37×10^{-7}
HDD_{65}	1.63	10.1	3.81×10^{-6}	1.14	3.53	6.42×10^{-3}	N/A	N/A	N/A

For the houses with buried and encapsulated ducts, two scenarios were investigated: adding blown-in insulation only around the ductwork, and adding blown-in insulation over the entire attic plane. In the first scenario, the additional insulation was ignored and the attic insulation was modeled at the same level as the pre-retrofit case. For the second scenario, 12 in. of additional blown-in attic insulation was assumed for an additional insulation level of R-30. At House 2, where the ducts were already partially buried, the additional insulation raises the R-value only from the existing R-24 to R-25.

The energy savings are relatively robust at 8% to 20% of total annual energy. These scenarios are compared to the alternative method of reducing duct losses by converting the attic to an unvented attic. House 2 was not modeled using this method because the location of the AHU precludes an accurate estimate of the duct losses. Without actually installing this configuration, duct leakage cannot be estimated.

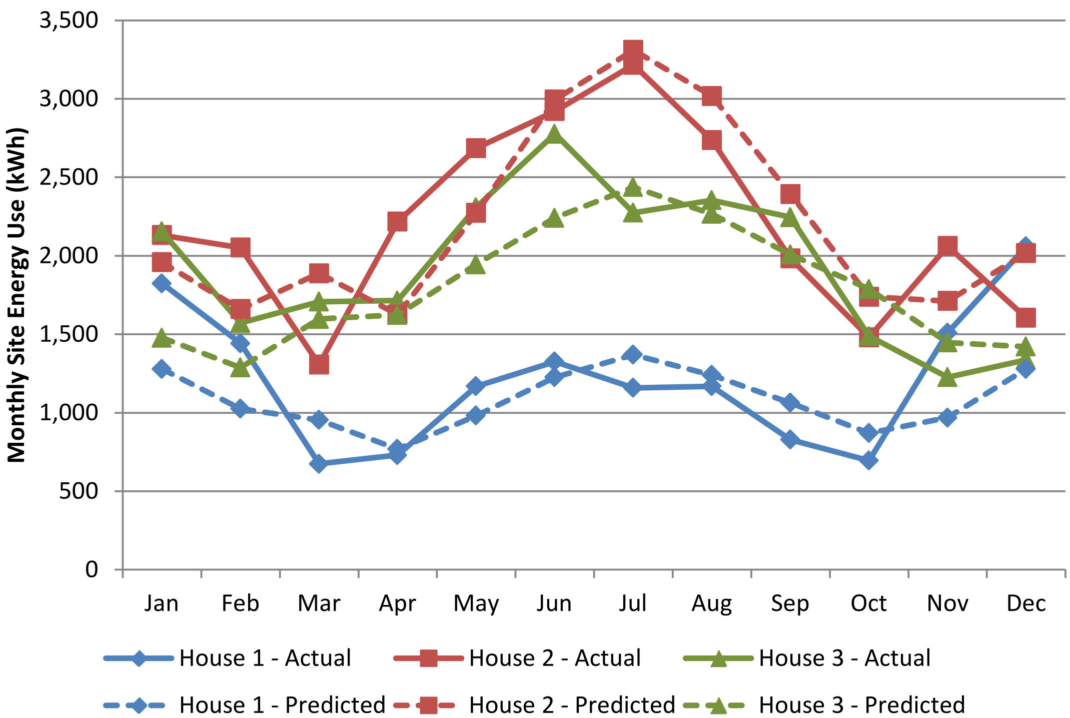


Figure 50. Predicted versus actual pre-retrofit energy use

These savings are reasonable in comparison to the predicted cooling and heating energy savings derived from the ASHRAE 152 seasonal delivery system efficiencies (Table 26). The predicted energy savings level from BEopt is consistently higher than that predicted by ASHRAE 152. Since these methods are both analytical estimates of the savings, it is difficult to determine which is more accurate.

Table 25. Predicted Energy Savings From BEoptE+ 1.2

	House 1			House 2		House 3	
	Encap-sulated + Mounded Buried	Encap-sulated + Fully Buried	R-30 Unvented Attic	Encap-sulated + Mounded Buried	Encap-sulated + Fully Buried	Encap-sulated	R-30 Unvented Attic
Annual Site Energy Savings (kWh)	1,013	1,365	777	4,566	5,203	1,032	1,190
% Savings Over Existing	8	10	6	17	20	5	5
Annual Utility Bill Savings Over Existing ($)	127	171	97	571	650	129	149

Table 26. Comparison of Predicted Savings Between BEopt and ASHRAE 152 (Duct Retrofit Only)

	Percent Predicted Energy Savings from ASHRAE 152 (Seasonal DSE)		Percent Predicted Energy Savings from BEopt	
	Cooling	Heating	Cooling	Heating
House 1	10.99	10.53	14.21	11.88
House 2	21.52	19.77	23.34	26.36
House 3	11.34	12.37	12.43	17.07

[a] This includes the added duct R-value of burying ducts at houses 1 and 2, but it excludes the additional R-value of the ceiling assembly after burial.

Table 27 shows the installed costs of the retrofits. These costs were derived from the HVAC and insulation contractor invoices for labor and materials, with the exception of the ccSPF insulation. The ccSPF costs are based on material and equipment data found in RSMeans (2011). The ccSPF was donated by the manufacturer, a partner in this project. As a result, actual ccSPF costs were not available but data on ccSPF quantities were used.

Table 27. Installed Cost of Encapsulated and Buried and Encapsulated Ducts at Houses

	House 1	House 2	House 3
Ductwork Area (ft^2)	483	719	280
Attic Insulation Area (ft^2)	521	521	N/A
Installed Cost ($)	2,990	3,806	956

The costs given in Table 27 represent the costs associated with this demonstration project. Not having undertaken this retrofit before, the contractor pricing is assumed to reflect time needed for training, setup, and coordination. These costs, however, do not include time required for coordination among the contractors and with the homeowners, which was carried out by the Building America team.

For the cost analysis, the researchers assumed that the installed costs will decrease as this becomes a widespread practice. The cost estimates for the measures shown in Table 28 assume that this retrofit is a mature building practice and processes are streamlined. The cost estimates are derived from the National Renewable Energy Laboratory's (NREL's) National Residential Efficiency Measures Database, RSMeans (2011), and the invoices from the contractors that performed the installation for this project. Again, no costs associated with coordination were included in these estimates.

Costs for the duct spray foam were taken from RSMeans and multiplied by 1.75 to account for the increased difficulty of the installation, material waste, and greater inconsistency of the application. Contractor invoices were used for comparison, but the cost estimates reflect average pricing and assume that the process has been streamlined. The projected costs, rather than the actual, were used for the cost-effectiveness analysis calculations.

Annualized returns were calculated assuming a 30-year analysis period, a 3% inflation rate, a 3% real discount rate, and a 7% 5-year loan. The lifetimes of the ducts and insulation were assumed to be 30 years. The cost savings are shown in Table 29. Encapsulated and buried and encapsulated ducts were shown to be cost effective; converting the attic to an unvented attic, though, was not cost effective. Generally, the added benefit of completely covering the attic plane with loose-fill insulation was not more cost effective than mounded burial of the ducts.

Houses 1 and 3 have no return ducting, which is common for Florida houses. Many Florida houses have AHUs in mechanical rooms with louvered doors with the bottom of the AHU open. Another alternative is that the AHU sits on top of a return plenum with a return grille directly below a closet door. As a result, the total costs and benefits of the measure are reduced for this case. House 2 presents the alternative where there is return ducting, leading to greater energy savings at a higher cost.

Table 28. Cost Estimates for Duct Retrofits

	House 1			House 2		House 3	
	Encapsulated + Mounded Buried	Encapsulated + Fully Buried	R-30 Unvented Attic	Encapsulated + Mounded Buried	Encapsulated + Fully Buried	Encapsulated	R-30 Unvented Attic
Ductwork Area (ft^2)	483	483	483	719	719	280	280
Attic Insulation Area (ft^2)	521	2,097	2,541	521	2,086	N/A	2,315
Duct Spray Foam ($1.89/ft^2) (RSMeans × 1.75)	$912	$912	N/A	$1,358	$1,358	$530	N/A
Blown-in Insulation ($0.63/ft^2) (NREL 2012)	$328	$1,321	N/A	$328	$1,314	N/A	N/A
Roof Deck Spray Foam ($3.58/ft^2) (NREL 2012)	N/A	N/A	$9,096	N/A	N/A	N/A	$8,287
Remove Blown-in Insulation (Contractor Cost)	N/A	N/A	N/A	$756	$756	N/A	N/A
Seal Boots and Place Rigid Insulation (Contractor Cost)	$63	$63	N/A	$84	$84	$63	N/A
Duct Reconfiguration (Contractor Cost)	$426	$426	N/A	$864	$864	N/A	N/A
Total Cost ($)	**$1,730**	**$2,722**	**$9,096**	**$3,391**	**$4,376**	**$530**	**$8,287**

Table 29. Annualized Savings by Retrofit Measure and House ($)

	House 1			House 2		House 3	
	Encapsulated + Mounded Buried	Encapsulated + Fully Buried	R-30 Unvented Attic	Encapsulated + Mounded Buried	Encapsulated + Fully Buried	Encapsulated	R-30 Unvented Attic
Total Cost	1,730	2,722	9,096	3,391	4,376	530	8,287
Utility Bill Savings	127	171	97	571	650	129	149
Annualized Savings	10	–28	–821	513	209	141	–655

11 Conclusion

This report takes a multifaceted approach, including field testing and analytical methods, to evaluate the cost effectiveness, energy savings potential, and condensation potential of encapsulated and buried and encapsulated ducts. Although field testing yielded valuable information about the installed system performance, variations in field conditions necessitated further analysis. As with any field testing of occupied homes, quantifying energy savings was difficult because of the dramatic changes in occupant behavior and building system performance. Despite these difficulties, field testing was necessary to establish data-driven support for other analytical methods. The following sections summarize the conclusions for each of the key sections of the report.

11.1 Retrofit Methodology and Lessons Learned

The retrofitting methodology used in this study was evaluated in terms of effectiveness, feasibility, and safety. Although the implemented methodology was effective, several issues must be more carefully considered in future installations, such as protecting existing materials, ensuring proper spray foam coverage, and coordinating among trades. Section 4 covers these topics in greater detail.

First, can lighting, exhaust fans, flues, security wire, plumbing, and other services located in or along the ceiling plane can get covered in foam and/or require baffling for protection during the retrofit. Second, training is required to emphasize the importance of ensuring that the minimum application thickness of the ccSPF (1.5 in. at R-6.7 h-ft^2-°F/Btu-in.) is consistently achieved to mitigate the potential for condensation. In areas where applying ccSPF is difficult, such as the undersides of ductwork too low to reach with the spray nozzle, ensuring proper installation is important. Two options can be used to solve this problem. The installer can cocoon the duct in ccSPF and directly seal it to the sheetrock. Alternatively, a piece of rigid insulation can be inserted under the ductwork to serve as a substrate for the foam and ensure that the minimal insulation thickness is achieved on the underside of the ducts.

Finally, coordination between trades must be considered. The buried and encapsulated duct strategy is a multitrade effort. To offer this strategy as a package, two or three contractors would be required: a ccSPF installer, a blown-in insulation installer, and an HVAC installer. (The latter might be optional depending on local codes). This strategy requires a significant amount of coordination, and this role should be assigned early in the process. The encapsulated duct strategy, on the other hand, is a single-trade effort, requiring significantly less coordination and fewer periods of access to the home. In addition, this strategy uses a single insulation material and costs less.

11.2 Field Evaluation

Changes in the mechanical and distribution system configuration and operation at each house created challenges for interpreting long-term field monitoring and performance testing data. Despite these challenges, the data gave interesting insights into duct system performance and validated the calculated system performance. These topics are discussed in greater detail in Section 5.

Field testing and monitoring showed promising improvements in system performance. Duct leakage rates were reduced considerably. At the same time, airflows remained relatively constant in both pre- and post-retrofit testing. The R-value of the encapsulated-only ductwork was approximately half that of the buried and encapsulated ductwork. A qualitative analysis of the monitoring data showed a large improvement in duct R-values and no worsening of any existing condensation potential.

11.3 Effective and Apparent R-Values

In order to calculate heat transfer gains and losses from ductwork in unconditioned attics, effective and apparent R-values were calculated using several techniques. Section 6 provides greater detail on these calculations. Analytical calculations were used to determine the effective and apparent R-values of traditional ductwork and encapsulated ducts. Because buried and buried and encapsulated ducts are more complex than traditional insulation systems, a finite-element heat transfer analysis was required to calculate these values for the buried duct strategy.

The resulting R-values from both methods matched existing literature well and showed large improvements in R-values for encapsulated and buried and encapsulated ducts. The calculations found that, by encapsulating the ductwork in 1.5 in. of ccSPF (R-6.7 h-ft^2-°F/Btu-in.), the existing R-4.2 flexible ductwork can be improved to values between R-9 and R-13, depending on the size of the duct. Comparable buried and encapsulated ducts will have a significantly higher increase in R-values, ranging between R-16 and R-31.

11.4 Effective Heat Transfer Coefficients

The calculated R-values listed in Section 6 were validated using field monitoring data in Section 7. The reduction in apparent UA values, based on field data, correlated well with the theoretical UA value reduction that was developed based on the analysis in Section 6. The values were found to be within 10% of one another, which is a reasonable alignment given that the calculation assumes steady-state operation.

11.5 ASHRAE Standard 152 Distribution System Efficiency

Based on the field monitoring and analytical tools used in Section 6 and validated in Section 7, both DE and DSE were calculated for the three test homes. The calculations show that duct leakage has a significant impact on DE, resulting from the direct relationship between duct leakage and duct losses. Duct leakage rates were substantially reduced through encapsulation with ccSPF. Duct leakage to the outdoors was reduced to minimal rates typical for houses with AHUs in the living space. For the house with an AHU in the garage, the duct leakage rates were dramatically reduced, but still significant.

The heating and cooling seasonal DSEs for the best-performing buried and encapsulated duct home were 97% post-retrofit, compared to pre-retrofit percentages of 85% and 86%, respectively. The heating and cooling seasonal DSEs for the home with the encapsulated-only system were 95% and 91%, respectively, after the retrofit. These values were compared to 85% and 81% pre-retrofit, respectively. The pre-retrofit seasonal DSEs for the two homes with flexible ductwork were similar (85%–87%). Post-retrofit, the heating seasonal DSE was 2% higher when the ducts were buried. Similarly, the cooling seasonal distribution system efficiency was 6% greater in the home where the ducts are buried.

The pre-retrofit seasonal DSE for the home with ductwork constructed primarily of duct board was 65% for heating and 54% for cooling. This is roughly 20% lower than the flexible duct systems. This is reasonable, based on the condition of the existing ductwork, the presence of an unsealed duct opening, and the high duct leakage rates. Post-retrofit, the heating seasonal DSE was 21% higher when the duct board system was encapsulated and buried. Similarly, the cooling seasonal DSE was 25% greater after the retrofit and duct repair.

11.6 Condensation Potential of Buried and Encapsulated Ducts

In Section 9, the steady-state two-dimensional thermal model developed in Section 6 was combined with one-dimensional dynamic hygrothermal model to predict the potential for condensation on the surface of the duct. This analysis was conducted for buried ducts and buried and encapsulated ducts using the worst case configurations. The results from the analysis predict condensation issues for the buried ducts without additional ccSPF insulation. Griffiths et al. (2002) observed these issues as well. The closeness of duct surface temperature and the dew point of the surrounding air at the bottom of the duct confirmed the need for a minimum insulation level of 1.5 in. of ccSPF on ducts with R-4.2 insulation.

11.7 Predicted Energy and Cost Savings

In Section 10, predicted energy savings were based on a calibrated BEopt model. The BEopt energy savings, which ranged from 5%–20% of total energy use for the three houses, appear reasonable in comparison to the predicted cooling and heating energy savings derived from the ASHRAE 152 DEs (ASHRAE 2004). A cost-effectiveness analysis determined that the buried and encapsulated duct retrofit achieved $10 in annualized savings, making it cost effective (greater than zero). The encapsulated-only strategy has $141 in annualized savings. The higher cost effectiveness of the encapsulated-only strategy is due, in part, to avoiding the material and labor requirements associated with duct reconfiguration and blown-in insulation. Although the encapsulated duct strategy was the most cost effective, the buried and encapsulated duct strategy has the largest amount of predicted energy savings.

11.8 Summary

Based on this research study, encapsulated and buried and encapsulated ducts were found to dramatically improve the DSE of existing ductwork. Pre- and post-retrofit DSEs were calculated using ASHRAE 152. The best case scenario estimates a DSE range of 97%–98%. Potential energy savings ranging from 5% to 20% per year were predicted through simulation. Both encapsulated and buried and encapsulated ducts were found to be cost effective.

Encapsulated ducts were found to be more cost effective than buried and encapsulated ducts to reduce energy costs associated with ductwork delivery losses. The encapsulated method is less expensive to install than buried and encapsulated ducts because it does not require an HVAC contractor to cut down and reconfigure the ductwork, nor does it require labor and material associated with loose-fill insulation for duct burial. Eliminating the need to reconfigure the ductwork also mitigates concerns about affecting the airflows in the home.

As a single-trade method, encapsulation requires fewer visits to the home and no coordination with other contractors. This is significant because a multitrade method requires sales coordination among differing trades to market the service, as well as field coordination for implementation. Encapsulated ducts, though, do require an appropriately fire-rated ccSPF to be code compliant, and the predicted energy savings are slightly lower. For new construction projects and gut rehab projects that include duct replacement, a buried and encapsulated duct strategy can result in additional energy savings with minimal additional effort. In these scenarios, the incremental installation costs are lower and more trades will already be involved in the project.

This research has been incorporated into the U.S. Department of Energy (DOE) Challenge Home National Program Requirements (DOE 2012). Under Section 10(c), buried and encapsulated ducts are exempt from the requirement that forced-air ducts be inside the home's thermal and air barrier boundary. Under this exception ductwork must be encapsulated with at least 1.5 in. of ccSPF and buried under 2 in. of blown-in insulation.

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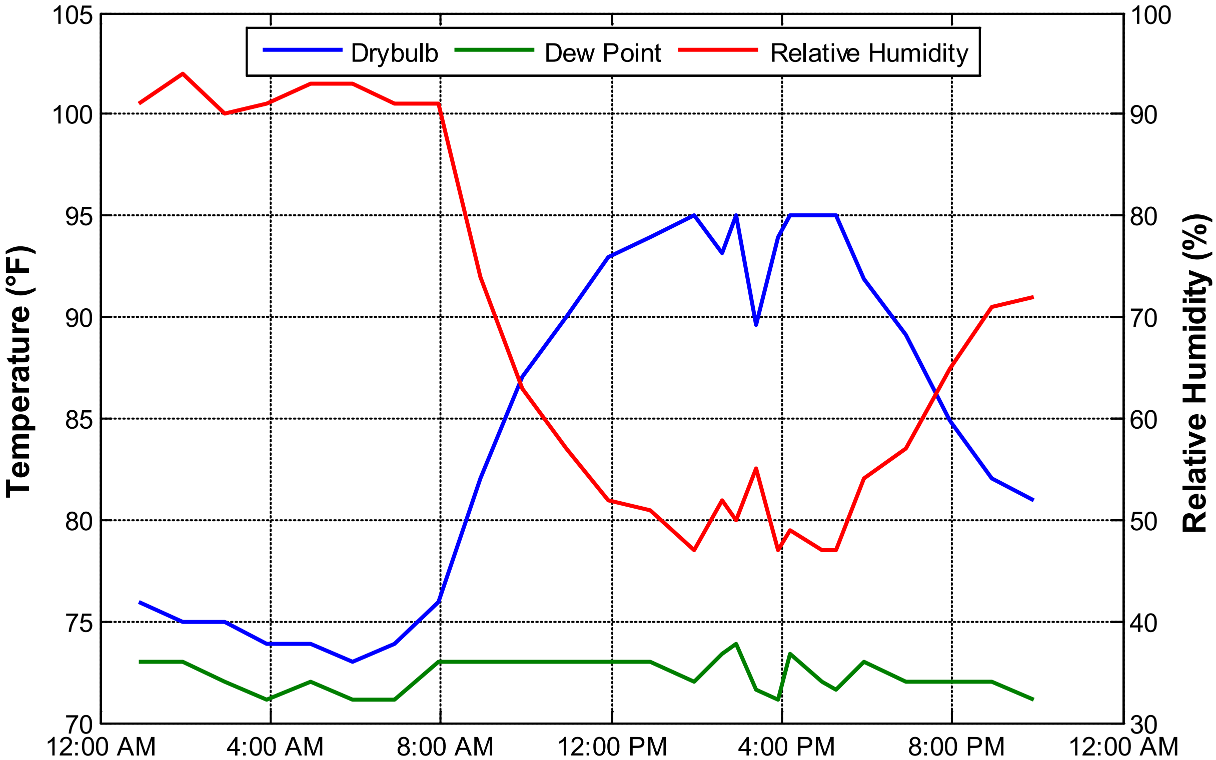
Appendix A: Attic Dew Point Temperature

This study yielded some intriguing insights into the moisture performance of attics in hot-humid climates. The dew point temperatures of the attics do not seem to track to outdoor dew points. Although the mean ambient dew point temperature corresponding to the 1% design temperature at Jacksonville Naval Air Station is 70°F (ASHRAE 2009), the attic dew point in these houses reached into the upper 80s. Furthermore, the ambient dew point was relatively constant throughout the day, but the attic dew point in these houses dropped to around 60°F during the night. Figure 51 shows the ambient conditions in Jacksonville, Florida, on July 29, 2010, using data from NCDC. On that day the dew point temperature remained relatively constant between 70°F and 75°F. The attic dew points, though, fluctuated at a much larger interval, 50°F to 90°F, as shown in Figure 52 through Figure 53



Source: NCDC (2012)

Figure 51. Ambient conditions in Jacksonville, Florida, on July 29, 2010

This might be surprising at first glance, but the attic dew point temperatures measured in this study do not seem inaccurate. The relative humidity sensors used in the study have a rated accuracy of ±2.5% in an operating range of –40°F to 158°F. Although dew point is more sensitive to errors in relative humidity measurement at higher dry bulb temperatures, the rated inaccuracy does not account for the dew point trends. A long-term monitoring study conducted for the U.S. Department of Housing and Urban Development that included 20 houses in Florida found similar trends in attic dew point temperatures (Arena et al. 2010). Explaining the cause of the changing dew point temperatures in the attics of these houses is outside the scope of this study, but possible explanations include solar moisture drive, along with moisture storage and evaporation in the building components, especially wood. Figure 52 and Figure 53 show the temperature and relative humidity of the attic and ambient air at one house monitored in this study and one house monitored by Arena et al. (2010), respectively.

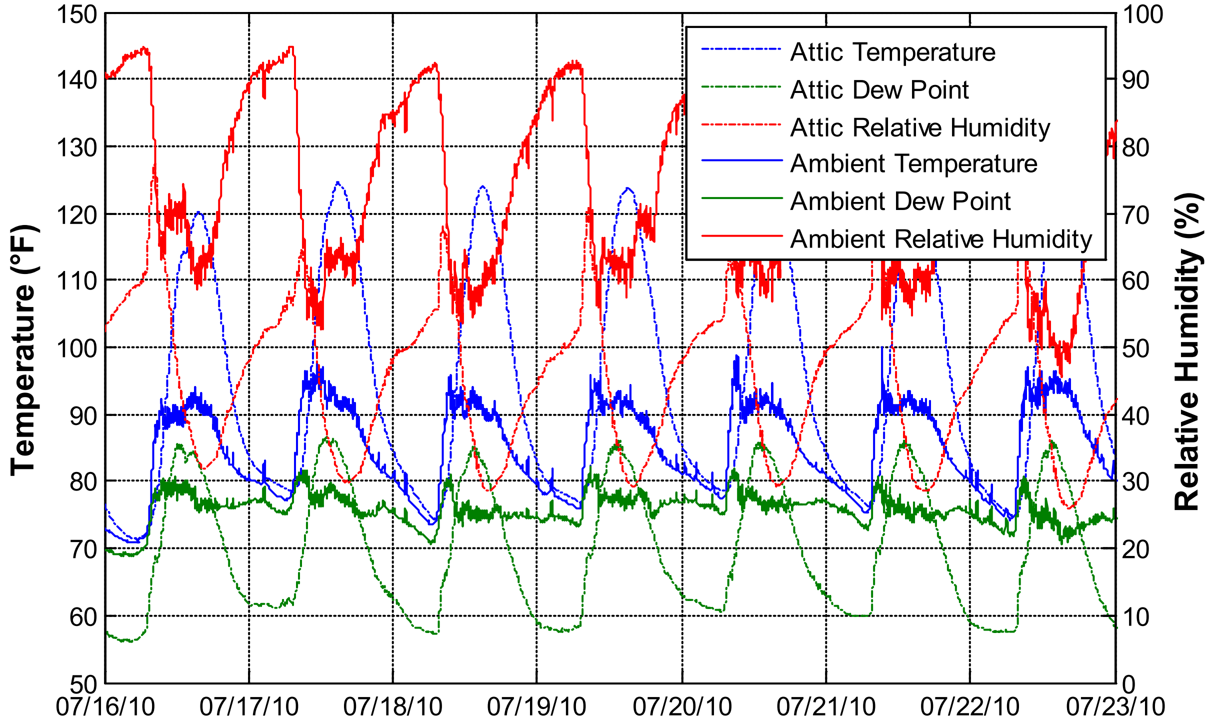


Figure 52. Pre-retrofit ambient and attic conditions at House 1

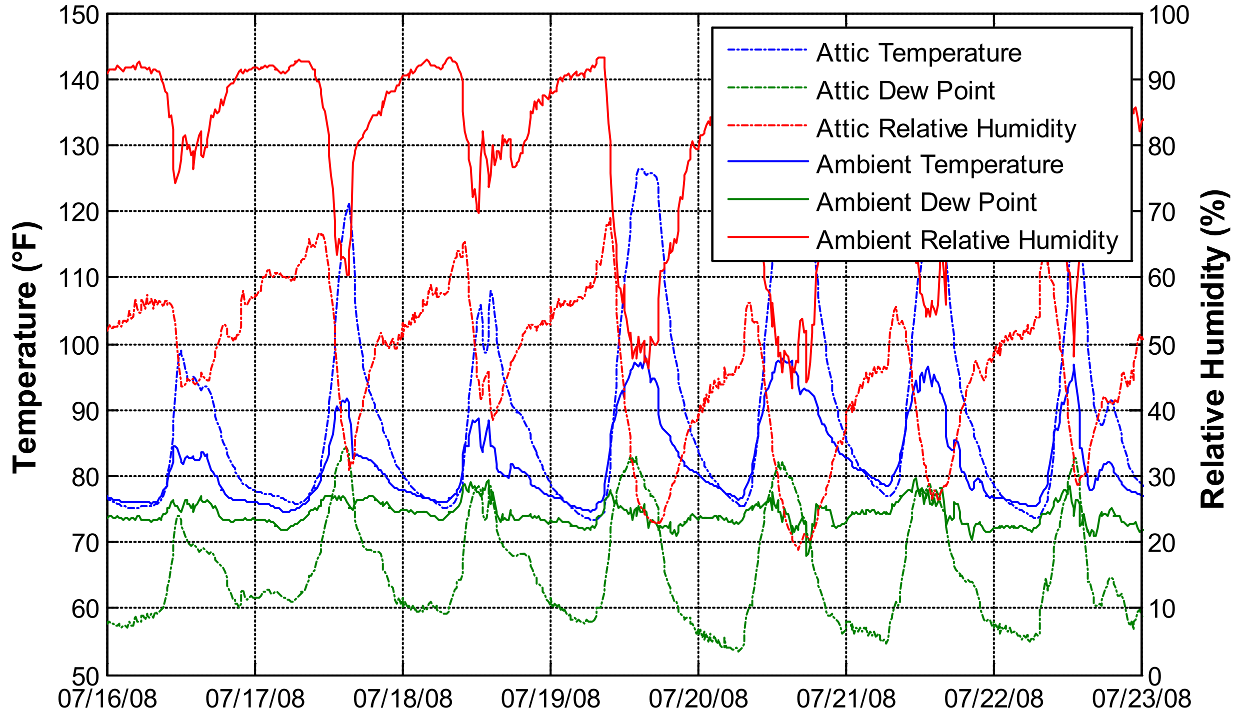


Figure 53. Ambient and attic conditions at U.S. Department of Housing and Urban Development Study House 4

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