Insulation Buried Attic Ducts: Analysis and Field Evaluation Findings

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ABSTRACT

The Building America program, funded by the Department of Energy, applies a systems engineering approach to residential construction. The ultimate goal is to improve energy and resource efficiency without increasing the builder's cost. A key element of the systems engineering approach for most Building America projects has been to improve space conditioning system efficiency by reducing or eliminating duct losses or gains. This paper presents the initial analytical work and preliminary findings from the subsequent field evaluation to quantify the energy benefits of burying ducts under loose fill attic insulation. This research was conducted by the Consortium for Advanced Residential Buildings (CARB), one of five Building America industry teams,

An analysis was done to determine the R-value of insulation wrap that conventionally hung ducts would require to achieve an equivalent thermal performance to insulation-buried ducts. These results formed the basis for a credit for buried ducts to be incorporated in the next round of revisions to California's Title 24.

A field evaluation involving side-by-side houses, one with buried ducts and one with conventionally hung ducts, was initiated in September 2003 to verify and expand upon the analyses results.

Introduction

A key element of the systems engineering approach for most Building America projects has been to improve space conditioning system efficiency by reducing or eliminating duct losses or gains. This research investigates the potential of burying attic ducting in loose-fill ceiling insulation to enhance forced air heating and cooling distribution efficiency. Other alternatives, including locating ducting in cathedralized attics or other conditioned space, have proven to be difficult to implement and generally unpopular with production builders. In combination with duct sealing, the "buried duct" approach has great promise for becoming the standard method of duct installation and substantially improving performance.

Several studies performed more than a decade ago revealed the significant impact that residential distribution system inefficiencies could have on the overall space conditioning system efficiency (Cummings et al. 1990, Modera 1989, Palmiter and Bond 1992, Proctor and Pernick 1992, Robison and Lambert 1989). Andrews (Andrews, 2003) summarizes the findings of earlier research by stating "that duct systems in unconditioned spaces typically lose 25% to 40% of the energy output from the space-conditioning equipment, with leakage and conductive losses contributing comparable amounts." More recently, much research has been conducted to support the development of Standard 152P (ASHRAE 2003), a test method for determining residential thermal distribution system efficiencies.

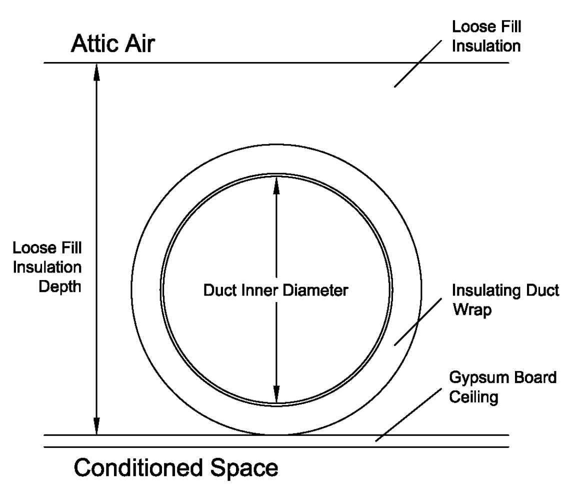
Through education and conservation programs, progress has been made in many regions to improve duct system tightness and reduce the inefficiency associated with duct leakage (DOE 1999). With greater emphasis on duct air sealing and the use of mastic, spurred in part by stricter energy codes, low air leakage duct systems are attainable (Hoeschle and Chitwood 2003). The authors do not advocate the attic insulation buried approach unless the ducts are tight. Leaky ducts should simply not be installed in vented attics.

With duct leakage under control, conductive energy losses have become a greater fraction of the total distribution inefficiency, and are therefore a prime target for further efficiency improvements. It should also be noted that these conductive losses are greatest during peak load conditions.

Analytical Research

To help quantify the energy benefits of the buried duct concept, initial analytical work utilized a two-dimensional steady state finite element heat transfer model (shown schematically in Figure 1). Several duct sizes and insulation depths were modeled as well as whether the duct rested directly on the ceiling gypsum board or on the bottom chord of the roof truss. Radiant heat transfer effects were not accounted for in this analysis. Since hung ducts have greater exposed surface areas than buried ducts for a given insulation depth, the omission of radiant heat gains results in a conservative estimate of the thermal performance benefits of burying the ducts. This research is more thoroughly presented in a recent ASHRAE paper (Griffiths and Zuluaga 2004).

Figure 1. Schematic of Configuration Modeled



For a conventional hung duct, the duct UA is expressed as:

$$UA_{duct} = Q_{duct}/(T_{attic} - T_{duct}) \quad (1)$$

where

Q_{duct} = *duct heat gain,*

T_{attic} = *attic temperature, and*

T_{duct} = *conditioned air temperature within the duct.*

To evaluate the energy benefits of buried ducts, it is useful to be able to determine the equivalent R-value that conventional hung ducts must be wrapped with to achieve the same thermal performance as buried ducts. Such an R-value can not simply be calculated by taking the inverse of the buried duct UA since Q_{duct} is now composed of two components: the detrimental heat gain from the attic (Q_{attic}) and the non-detrimental heat gain from the conditioned space below (Q_{room}):

$$Q_{duct} = Q_{attic} + Q_{room} \quad (2)$$

where

Q_{attic} = *the portion of duct heat gain between the conditioned duct air and the attic air, and*

Q_{room} = *the portion of duct heat gain between the conditioned duct air and the room air.*

Therefore, when comparing to attic hung ducts, the detrimental heat gain of concern is simply the Q_{attic} portion of the total duct gain. At constant duct and room air temperatures, Q_{attic} is a function of T_{attic} while Q_{room} is constant. Although Q_{room} is typically much smaller than Q_{attic}, it cannot be neglected in the buried duct energy balance. The finite element analysis assumed that the space conditioning system is adequately sized to maintain room conditions for any and all attic conditions. The thermal analysis results for Q_{duct} as a function of the attic and duct temperature difference – with room and duct temperatures constant – can be expressed as the linear equation:

$$Q_{duct} = UA_{eff}(T_{attic}-T_{duct}) + Q_{room} \quad (3)$$

The effective duct R-value is indicated by the slope of this linear relationship, UA or A/R. This effective value is the R-value that a conventionally hung duct must be wrapped with in order to result in an equivalent amount of detrimental heat gain. Q_{room}, over the range of practical temperatures, does not affect the R-value even though it is a component of the energy balance.

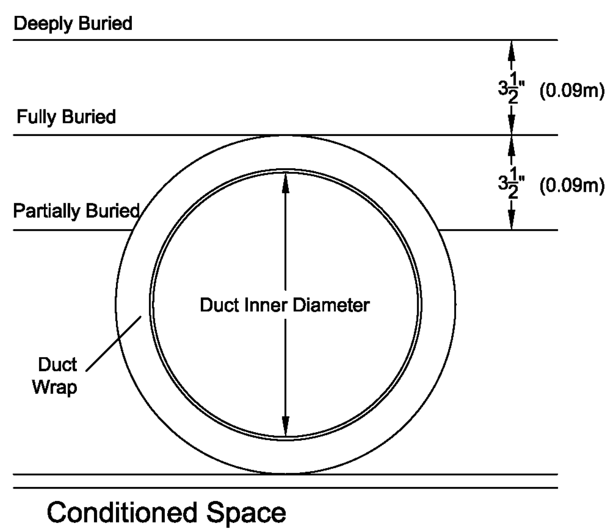
Analytical Results and Discussion

Applying the analysis technique described above, effective duct R-values were calculated for a variety of insulation and duct configurations. More specifically, whether the duct is "deeply", "fully", or "partially" buried was examined as well as duct sizes and whether the duct was resting on the gypsum board ceiling or run over the attic truss chords.

The thermal conductivity of the loose fill insulation can be varied to represent either loose fill fiberglass or cellulose. The thermal conductivity of loose fill cellulose and fiberglass depend on their blown in density. The R-value of loose fill fiberglass can vary from 2.2 ft^2-h-°F/Btu per inch to 2.9 ft^2-h-°F/Btu per inch, while the R-value of loose fill cellulose can range from 3.1 ft^2-h-°F/Btu per inch to 3.7 ft^2-h-°F/Btu per inch (ASHRAE 2001). For this study, average values of 2.5 ft^2-h-°F/Btu per inch for fiberglass and 3.4 ft^2-h-°F/Btu per inch for cellulose were used.

In this study, "deeply buried" indicates that the depth of the loose fill insulation is 3.5 inches higher than the top of the insulating duct wrap. "Fully buried" indicates that the depth of the loose fill insulation is even with the top of the insulating duct wrap. "Partially buried" indicates that the depth of the loose fill insulation is 3.5 inches lower than the top of the insulating duct wrap. The duct wrap is 1.25 inches thick with an R-value of 4.2 ft^2-h-°F/Btu representing standard construction practice at the time of this study. A schematic illustrating these classifications is presented in Figure 2.

Figure 2. Buried Duct Classification



It is noteworthy that when a 10-inch duct is *fully* buried under 12.5 inches of insulation, the effective duct R-value is nearly the same whether the 12.5 inches of insulation is fiberglass or cellulose. However, an attic R-value of 40 ft^2-h-°F/Btu with fiberglass requires a depth of 16 inches which *deeply* buries a 10-inch ID duct. The effective duct R-value is much higher than when the same duct is buried in an R-43 cellulose that requires a depth of only 12.5 inches. The conductive paths from the sides of the duct increase significantly as the burial depth increases. Thus, the critical parameter to maximizing the effective R-value of a buried duct is the degree that it is buried, not the attic R-value. It has been assumed that the attic insulation is blown to a uniform depth, which is what inspectors like to see. Since for the same attic R-value a greater depth of fiberglass is required, it is clear that fiberglass is a better material than cellulose for burying the ducts.

Raising a duct out of the attic insulation by resting it on either a 2-inch x 4-inch engineered truss chord or 3.5 inches of loose fill insulation results in a 50% reduction in effective R-value compared to when that duct is more deeply buried when in contact with the gypsum board. This significant penalty in the effective duct R-value underscores the benefits of designing a low profile duct system.

Guidelines have been developed to assess the effective R-value of a buried duct system. These became the basis for Table R4-12 in the *2005 Residential ACM Manual* (CEC 2003) and are presented in Table 1. Simulation results from small ducts and large ducts were combined so that these guidelines are applicable to ducts of all sizes commonly encountered in residential applications. This simplification is valid since for a particular buried duct classification, the impact of duct size on effective R-value was found to be small.

Table 1. Guidelines for Effective Buried Duct System R-values (ft^2-h-°F/Btu)

Loose Fill Insulation Type	**Buried Duct Classification**		
	Deeply	Fully	Partially
Fiberglass	25	13	9
Cellulose	31	15	9

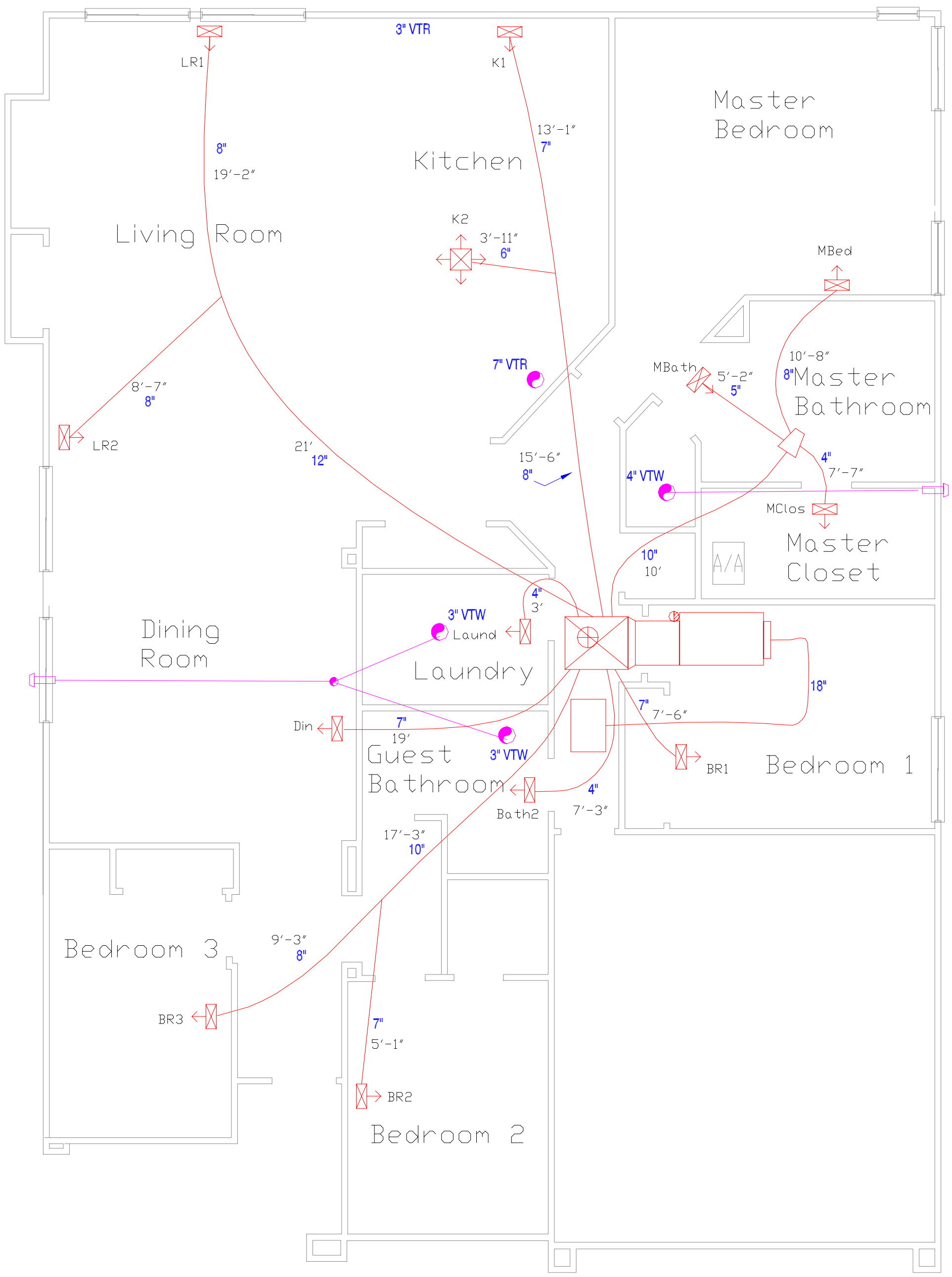
The analysis reported here has omitted the impact of radiant heat transfer which should, in most instances, make these results conservative. Further research is underway to quantify the impacts of radiant heat transfer.

Field Test Methods and Results

A field test to substantiate the analytical findings was initiated in the fall of 2003. Two houses were contributed by production builder DR Horton, one to serve as the buried duct test case and one as a control. The 2070 ft^2 single story homes have identical floor plans and are located within one block of each other in the Shadowbrook development in Elk Grove, California (near Sacramento). The control house faces south and the buried duct house faces north. Because the two plans are mirror images of each other, the east-west elevations are identical with respect to glazing area and wall surface area. Figure 3 presents the floor plan with the duct layout for the buried duct house.

Both houses have identical mechanical equipment and attic insulation specifications. The insulation product used was loose fill fiberglass with a manufacturer's listed R-value of 32 for the 12 inches of insulation installed. Duct lengths and diameters are the same for the two houses, the only difference being that in the control house, the ducts are hung. In fact, the workers installing the ducts for the two homes were apparently not informed of the change and initially suspended the ducts on both houses. They subsequently cut the strapping supporting the ducts in the buried duct home. The total leakage rates measured by duct pressurization at 25 Pascals were nearly identical for the two houses at just over 6% of total design airflow (1200 CFM).

Figure 3. House Plan with Buried Duct Layout



Three different measurement approaches were applied to the two homes to evaluate the benefits of the buried ducts. However, only one method has provided useful results to date. Attempts will be made to apply the other methods again under more controlled and ideal conditions.

The average duct R-value for the buried duct house was calculated using the worksheet developed for the California energy standards. These R-values were then used to estimate distribution efficiency using the ASHRAE 152P method. ASHRAE Standard 152P provides a method for estimating seasonal distribution efficiency of duct systems based on duct UA, location, leakage, and operating conditions. This standard can be used to estimate the performance improvement resulting from duct burial if effective duct U-values and other information are known.

Duct UA

Duct UA was estimated using observed duct surface area and R-value. R-values were determined using Table 2, which assumes R-30 attic insulation with a depth of 12 inches and R-4.2 wrapped ducts running over truss chords. Measured duct surface areas (inside) were divided by the R-values for each duct section and summed to obtain the overall UA using the worksheet process described in the Title 24 compliance option application. This calculation resulted in an average R-value of 6.0 for the buried duct case.

Table 2. Estimated Duct R-Values for R-30 Attic Insulation

Duct Diameter	Assumed Duct R-Value
4	13
5	13
6	13
7	9
8	9
10	4.2
12	4.2
14	4.2
16	4.2
18	4.2
20	4.2

Actual observations of duct coverage by insulation were used to complete a more detailed calculation of overall R-value. UA's for each duct run were calculated by summing the UA value for each duct section that was either deeply, fully, partially, or unburied. These data showed that the overall R-value calculated using this approach was 6.5, indicating the worksheet (Title 24) method is conservative in this case.

ASHRAE 152P Calculations

Distribution system seasonal efficiency was calculated using ASHRAE 152P methods from the data collected. Both measured average attic and duct temperatures and ASHRAE 152P default values were used to calculate distribution efficiency.

The only difference in inputs to the ASHRAE 152P method for the two houses is the supply duct UA value, since the return duct UA is the same. Using standard assumptions for seasonal attic temperatures and other variables, the calculated distribution efficiency increased by 5% from 0.858 for R4.2 ducts (UA = 123) to 0.902 for buried ducts (UA = 76).

If the attic temperature during the control house test of 111°F is used in the 152P calculation, a duct loss of 6670 Btuh is calculated. The measured duct loss during this test (from duct temperature drop data) was 6713 Btuh, suggesting that a simple UA – delta T calculation can yield results similar to ASHRAE 152P.

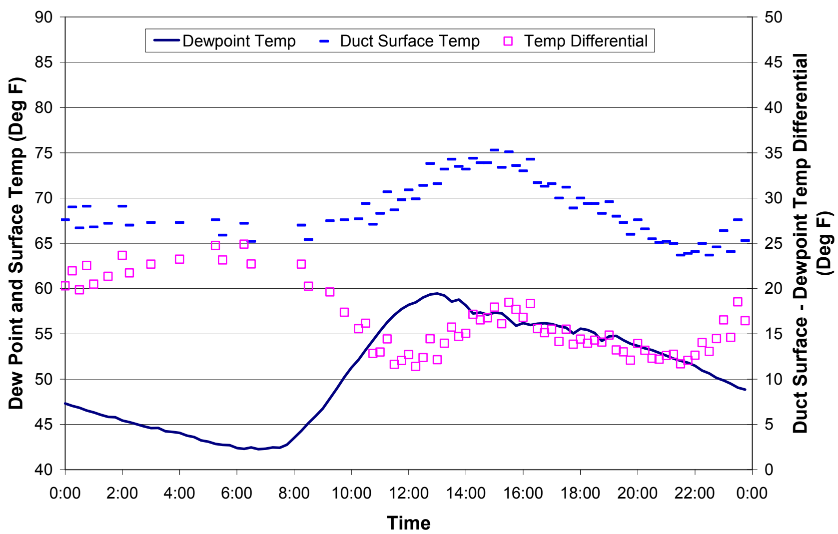
Dewpoint Evaluation

It should be emphasized that the buried duct concept, as presented here, is only appropriate for dry climates. Covering the ducts with insulation lowers the temperature at the vapor barrier jacket surface during summer months. In humid climates, this temperature could be below the dewpoint of the attic air and condensation could occur.

Long-term measurements were taken in the buried duct home to determine how closely the surface temperature of a fully buried duct would approach the dewpoint temperature. Measured attic dry-bulb temperature and relative humidity were used to calculate the dewpoint temperature, which was compared to measured duct surface temperature. The extensive use of the air conditioner by the owners provided an ideal test, since duct temperatures were depressed for extended periods of time.

Figure 4 shows the duct surface and dewpoint temperatures for a day with significant air conditioning operation. This would represent a period when duct surface temperatures would likely be lowest. The surface temperature is filtered so that it only shows the temperature when the air conditioner is running. At no time was the duct surface temperature less than 10° above the dewpoint temperature. These data indicate that condensation on duct surfaces is most likely not an issue in the Northern California central valley climate.

Figure 4. Daily Profile of Duct Surface and Dewpoint Temperatures



Summary

A finite element analysis model was developed to quantitatively study the energy benefits of ducts buried in loose fill attic insulation in dry climates. A technique was developed to determine the effective R-value that conventional hung ducts must be wrapped with to achieve the same thermal performance as buried ducts. This effective R-value could then be applied in energy simulation tools to assess the peak energy demand and annual energy use benefits of the buried duct concept.

Using this methodology, it was found that level of duct coverage is the defining factor for the effective buried duct R-value rather than attic insulation R-value. Also, whether the duct rests on the ceiling gypsum or a truss chord is only important with respect to the extent the duct is buried.

Three classifications for duct burial were defined – deeply, fully, and partially, and simplified guidelines for the effective duct R-value corresponding with these classifications were developed.

Field test results suggest that the methods proposed for Title 24 compliance provide a reasonably accurate estimate of duct performance and that duct condensation is not a risk in the Northern California central valley climate.

Acknowledgements

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