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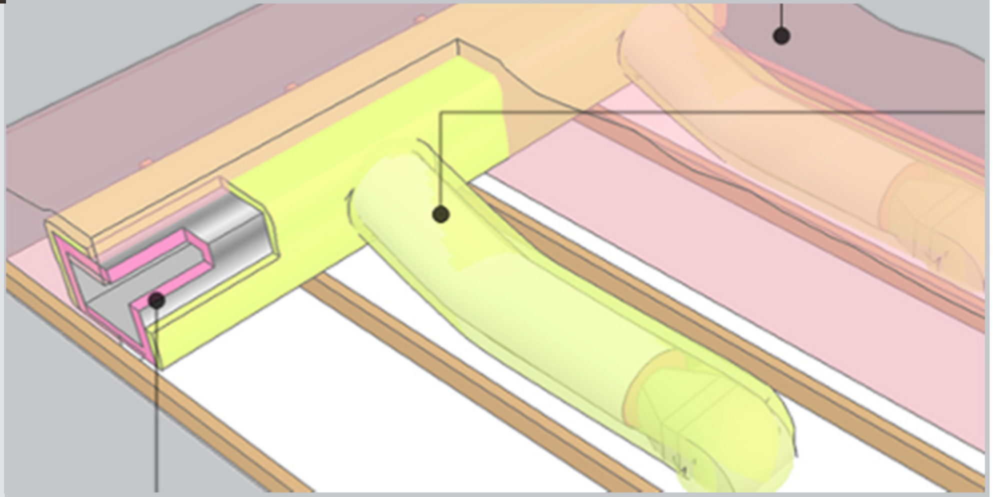
Measure Guideline: Buried and/or Encapsulated Ducts

C. Shapiro, W. Zoeller, and P. Mantha
Consortium for Advanced Residential Buildings

August 2013



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Definitions

AHU	Air handling unit
BA	Building America
BED	Buried and/or encapsulated duct
BPI	Building Performance Institute
ccSPF	Closed cell polyurethane spray foam
HVAC	Heating, ventilation, and air-conditioning
IECC	International Energy Conservation Code
IRC	International Residential Code
XPS	Extruded polystyrene

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Executive Summary

Buried and/or encapsulated ducts (BEDs) are a class of advanced energy efficiency strategies intended to address the significant ductwork thermal losses associated with ducts installed in unconditioned attics. BEDs are ducts installed in unconditioned attics that are covered in loose-fill insulation and/or encapsulated in closed cell polyurethane spray foam (ccSPF) insulation. This Building America Measure Guideline covers the technical aspects of BEDs as well as the advantages, disadvantages, and risks of BEDs compared to alternative strategies. Detailed guidance on installation of BEDs strategies in new and existing homes through step-by-step installation procedures is also provided

This guideline synthesizes previously published research on BEDs and provides practical information to builders, contractors, homeowners, policy analysts, building professionals, and building scientists. Some of the procedures presented here, however, require specialized equipment or expertise. In addition, some alterations to duct systems may require a specialized license.

This guideline provides valuable information for a building industry that has struggled to address ductwork thermal losses in new and existing homes. As building codes strengthen requirements for duct air sealing and insulation, flexibility is needed to address energy efficiency goals. While ductwork within the thermal envelope has been promoted as the panacea for addressing ductwork thermal losses, BED installations approach—and sometimes exceed—the performance of ductwork within the thermal envelope.

Acknowledgments

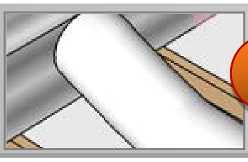
Steven Winter Associates, Inc. acknowledges the U.S. Department of Energy Building America program and its funding and support of development of this technical report as well as research that informed it.

Progression Summary: New Construction

Determine System to Install

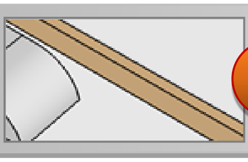
Determine whether to install typical ductwork, an interior ductwork system, or a BED method. If a BED method is going to be installed, proceed to step 1.

Design Duct System



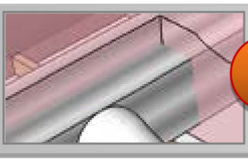
① Design a compact, low-profile duct system using industry-accepted best practices. The system should be oriented such that the greatest degree of duct burial can be achieved.

Determine Construction Sequence



② Determine whether the ceiling will be installed prior to duct installation.

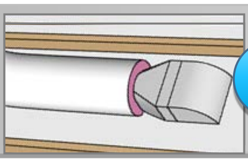
Determine Burial Depth



③ Based on the height of the duct branches and supply trunks and the height of the loose-fill insulation, determine the depth and category of burial. Increase loose-fill depth if higher performance is desired.

Install ceiling if ductwork will be installed after ceiling installation.

Install Ductwork

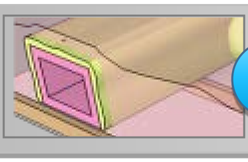


④ Install compact, low-profile duct system using R-8 insulated ducts. Mastic seal all connections, test duct leakage, and air seal ceiling plane penetrations prior to encapsulation or burial.

Encapsulate ductwork with at least 1.5 in. of ccSPF if BEDs are installed.

Install ceiling if ductwork was installed before ceiling installation.

Bury Ducts



⑤ Bury ductwork with loose-fill insulation. At least 1.5 in. of fiberglass must cover all ccSPF not rated for exposed attic installations.

Progression Summary: Existing Homes

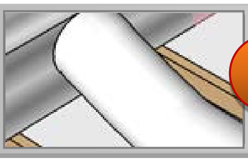
Inspect Home

Inspect the condition of the existing home and determine if there are health and safety issues in the home that prevent safe installation of a BED method.

Do not proceed if:

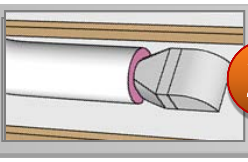
- The attic has active knob and tube wiring.
- The attic has asbestos, mold, or other contaminants.
- The attic has structural issues.
- The attic has insufficient access.

Survey Attic



1 **Survey and document the layout and condition of the existing ducts and attic insulation.**

Create Retrofit Plan

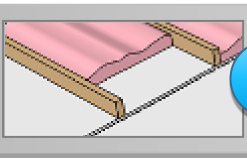


2 **Based on the configuration and condition of the ducts and attic, determine whether insulation and ductwork can be reused or must be reconfigured or replaced**

Install any needed temporary protection and access.

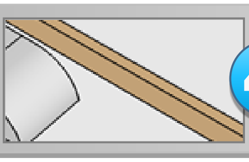
Relocate or reconfigure ducts to accommodate BED design.

Remove Insulation



3 **Complete duct and insulation removal as necessary**

Air Seal Attic



4 **Air seal attic ceiling penetrations.**

(Buried and) encapsulated ducts: Apply at least 1.5 in. of ccSPF insulation to all duct surfaces.

Buried (and encapsulated ducts): Bury ductwork with loose-fill insulation. At least 1.5 in. of fiberglass must cover all ccSPF not rated for exposed attic installations.

1 Introduction

Ductwork installed in unconditioned spaces—such as attics, crawlspaces, and garages—can contribute significantly to the overall heating and cooling costs of residential buildings. Estimated duct thermal losses for single-family residential buildings with ductwork installed in unconditioned spaces range from 10%–45% of total cooling and heating loads (Shapiro et al. 2012). As a result, poorly installed duct systems can account for almost half of the total heating and cooling costs of some residential buildings.

There are three primary methods, listed below, of reducing thermal losses associated with ductwork in unconditioned spaces. All of these methods are covered by the Building America (BA) Measure Guidelines described below. These methods have various cost, performance, safety, and practical tradeoffs that must be considered before implementation, but each can greatly improve heating and cooling system efficiencies.

- **Proper sealing and insulation of ductwork** can reduce thermal losses from ductwork to around 10%, but further reduction of duct thermal losses requires more advanced techniques. The proper techniques for sealing and insulating ductwork are covered in the Building America Measure Guideline *Sealing and Insulating Ducts in Existing Homes* (Aldrich and Puttagunta 2011).
- **Installing or moving ducts within the thermal envelope** can eliminate duct thermal losses entirely. Depending on the method employed, however, living space may be affected, and the building envelope load may be increased slightly. Installation of ducts within the thermal envelope is covered in the BA Measure Guideline, *Summary of Interior Ducts in New Construction, Including an Efficient, Affordable Method to Install Fur-Down Interior Ducts* (Beal et al. 2011).
- **Burying and/or encapsulating ductwork in attics** can reduce ductwork thermal losses to around 3% or less. Under this family of duct insulation approaches, ductwork may be encapsulated in closed-cell spray polyurethane foam (ccSPF) insulation and/or buried beneath loose-fill insulation. Buried and/or encapsulated ducts (BEDs) reduce duct thermal losses without affecting living space or increasing thermal envelope loads. This method is the subject of this guideline.

BEDs have been the subject of building science research for more than a decade, particularly through the BA program (CARB 2000; Griffiths et al. 2002; CARB 2003; Griffiths et al. 2004; Griffiths and Zuluaga 2004; Vineyard et al. 2004; Zoeller 2009; Shapiro et al. 2012). As a result of BA research, BEDs have been incorporated into several energy conservation codes and standards. For example, buried ducts are compliant, when properly installed, with Title 24 of the California Code of Regulations (CEC 2007, 2008), which governs construction of buildings throughout the state of California and stipulates minimum energy conservation levels (CBSC 2010). Spray foam encapsulated ducts are prescriptively allowed by the 2009 *International Residential Code* (IRC). As an alternative to interior duct installations, the U.S. Department of Energy's *Challenge Home National Program Requirements* allows ductwork in attics that is encapsulated with at least 1.5 in. of ccSPF and buried under 2 in. of loose-fill insulation (DOE 2012).

This guideline synthesizes previously published research on BEDs and provides practical information to builders, contractors, homeowners, policy analysts, building professions, and building scientists. Both existing homes and new construction are covered by this guideline. This guideline is split into three major sections. First, the technical aspects of BEDs are discussed in depth, including duct materials, insulation materials, encapsulated ducts, buried ducts, BEDs, effective R-values of these methods, and interactions with other systems. Second, the decision-making process is outlined through a discussion of the risks of BEDs and other methods of reducing duct thermal losses, and a comparison between the cost and performance of BEDs and other methods of reducing duct thermal losses. Finally, detailed step-by-step measure implementation instructions are provided for all BEDs methods in new and existing homes.

2 Technical Description

Conventional heating, ventilation, and air-conditioning (HVAC) design manuals dictate that space-conditioning air in cooling-dominated climates be discharged from ceiling or high wall registers (ACCA 1992). As a result, most houses in hot climates with ducted space-conditioning systems have ductwork, and in some cases air handling units (AHUs), in unconditioned attics. Energy losses from duct leakage to the outside, which commonly vary from as little as 3% to much more than 20%, are exacerbated by large temperature differentials between the conditioned air inside the duct and the air in the unconditioned attic. 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 supply air passing through attics with 20°F ambient attic air.

BEDs are a class of solutions that provide simple and cost-effective methods for reducing thermal losses from ductwork installed in unconditioned attics. There are three possible combinations under this strategy: (1) buried ducts; (2) encapsulated ducts (with ccSPF); and (3) BEDs. The best solution depends on the climate, age of the house, and the configuration of the HVAC system and attic. Ducts that are only encapsulated without burial are not recommended for new construction because additional burial requires only minor increases in planning and cost over encapsulation alone. Thus, BEDs yield significantly higher performance with minimal additional effort. Buried ducts without encapsulation should not be installed in moist or marine climates, because there is a risk of condensation on the surface of the ductwork.

2.1 Buried Ducts

Buried ducts involve placing ductwork as close to the ceiling as practical—either on top of the gypsum board ceiling or over the truss bottom cords—and burying the ductwork beneath loose-fill insulation. Any loose-fill insulation, such as fiberglass or cellulose, can be used for this strategy. When more loose-fill insulation is used to

Duct Materials[a]

The three most common duct materials are sheet metal, fiberglass duct board, and flexible duct. A duct distribution system may utilize a combination of these materials, such as sheet metal trunks off the AHU and flex-duct branches to supply the individual registers.

Flexible Duct

Flex duct is composed of three materials: (1) an interior polymer tube with diameters ranging from 4 in. to 24 in. supported by a spiral, metal coil; (2) fiberglass insulation with thicknesses ranging from 1 in. to 3 in.; and (3) an outer polymer liner, which usually incorporates a low-emissivity foil facing that provides a radiant and vapor barrier. This flexible composition means that flex duct is relatively inexpensive and comes pre-insulated. Furthermore, flex duct can be run longer distances—with several bends and turns—without additional fittings or connections. With fewer transitions and fittings, flex duct can be very airtight, but as with other duct materials, leakage problems can still occur at connections.

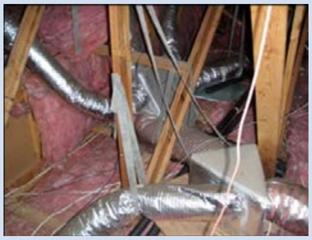


Figure 1. Insulated flex duct an existing home

[a] Text for some sidebars is derived from Aldrich and Puttagunta (2011).

boost the duct R-value, there is an added benefit of increasing the ceiling assembly R-value as well. See Figure 2 for a diagram showing a buried duct installation.

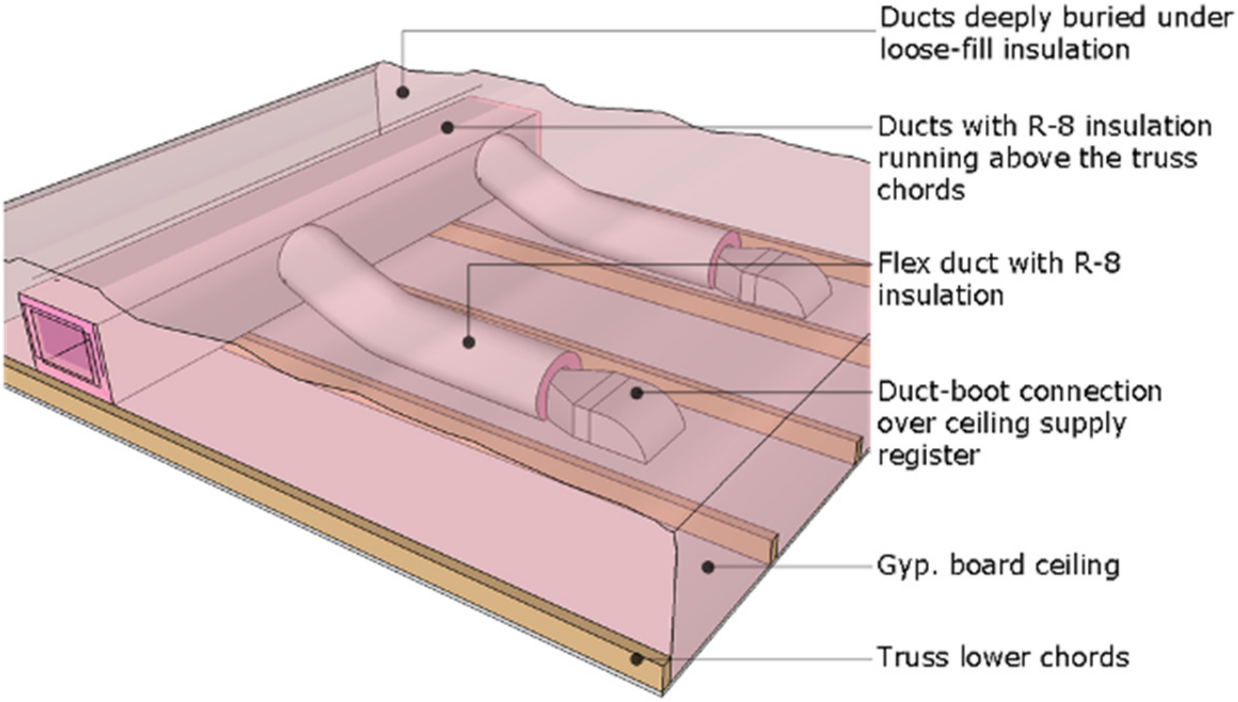


Figure 2. Diagram of buried ducts

For analysis purposes, buried ducts are categorized into three burial classes based on the distance from the top of the duct to the top of the loose-fill insulation: (1) partially buried; (2) fully buried; and (3) deeply buried. Partially buried ducts are buried to 3.5 in. below the top of the duct. Fully buried ducts are buried to the top of the duct. Deeply buried ducts are buried with 3.5 in. of loose-fill insulation over the top of the ductwork. See Figure 3 for a diagram showing the three burial classes.

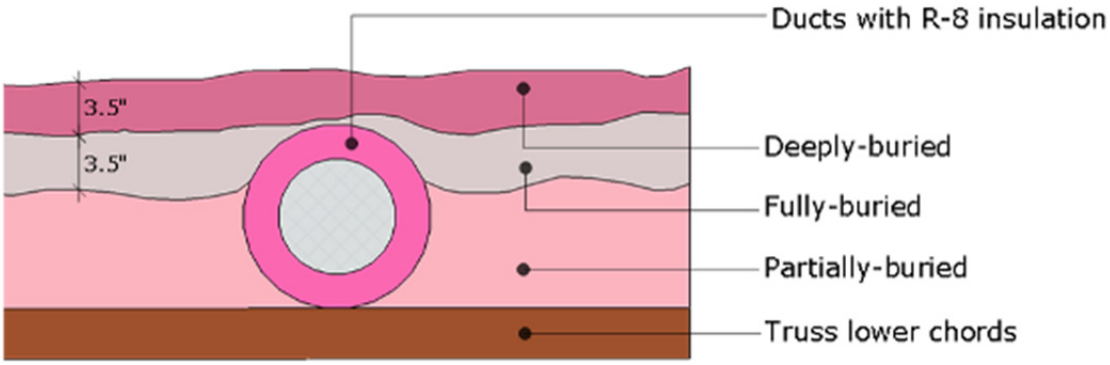


Figure 3. Categorization of buried duct insulation levels; not for moist and marine climates

Fiberglass Duct Board

Duct board is a rigid, dense, fiberglass sheet; the outside typically has a fiber-reinforced foil facing which acts as a vapor barrier. Duct board is usually sold in large sheets (e.g. 4 ft × 10 ft) with thicknesses of 0.75 in. to 2 in. The fiberglass provides thermal insulation and sound attenuation.

Duct board is typically cut, folded, and shaped into rectangular sections of duct. Duct board is primarily used for plenums, trunks, and junction boxes; smaller branch ducts can be sheet metal or, more commonly, insulated flex duct. The most common areas for leakage are at collars, transitions, and connections to other materials.

Figure 4. Fiberglass duct board ducts in an attic

Sheet Metal

Galvanized steel metal is a very common duct material and is required in some jurisdictions. Round and rectangular shapes are the most common, but ovals and other shapes are sometimes used. There is also a wide array of sheet metal fittings that connect sections of duct, such as elbows, transitions, takeoffs, and reducers.

Screws are typically used to connect straight round ducts to collars, elbows, Ts, Ys, reductions, boots, and other fittings. The Sheet Metal and Air Conditioning Contractors National Association recommends using at least three #8 sheet metal screws spaced equidistant (SMACNA 1998). If seams, gaps, and connections are not sealed before insulation, substantial leakage can result.

Figure 5. Sheet metal supply plenum

2.2 Encapsulated Ducts

Encapsulated ducts involve spraying ductwork with ccSPF to boost the R-value of the duct insulation and reduce air leakage (Figure 6). Although ccSPF may be applied directly to the exterior of uninsulated ductwork, insulation of ductwork with fiberglass duct wrap prior to encapsulation is a lower cost way to increase the duct R-value. Unlike buried ducts, where effective sealing of ductwork prior to burial is a must for proper installation, encapsulated ducts do not require the same level of rigorous air sealing. Ducts should be sealed to reasonable tightness, and ccSPF will act as an additional air barrier. In order to be code compliant, the ccSPF used must be approved for exposed attic installations. (See Section 2.4 below.)

Figure 6. Encapsulated duct in attic

2.3 Buried and Encapsulated Ducts

With buried and encapsulated, ducts are first encapsulated with ccSPF insulation and subsequently buried under loose-fill insulation. Initially conceived as a way to apply the buried ducts concept to humid climates (where condensation could occur on the outer surface of buried ducts), BEDs can also be used as a high-performance duct insulation strategy in all climates. BEDs have even higher R-values than buried ducts and include the air sealing benefits of encapsulated ducts. Figure 7 shows a diagram of BEDs, and Figure 8 shows the burial levels associated with BEDs.

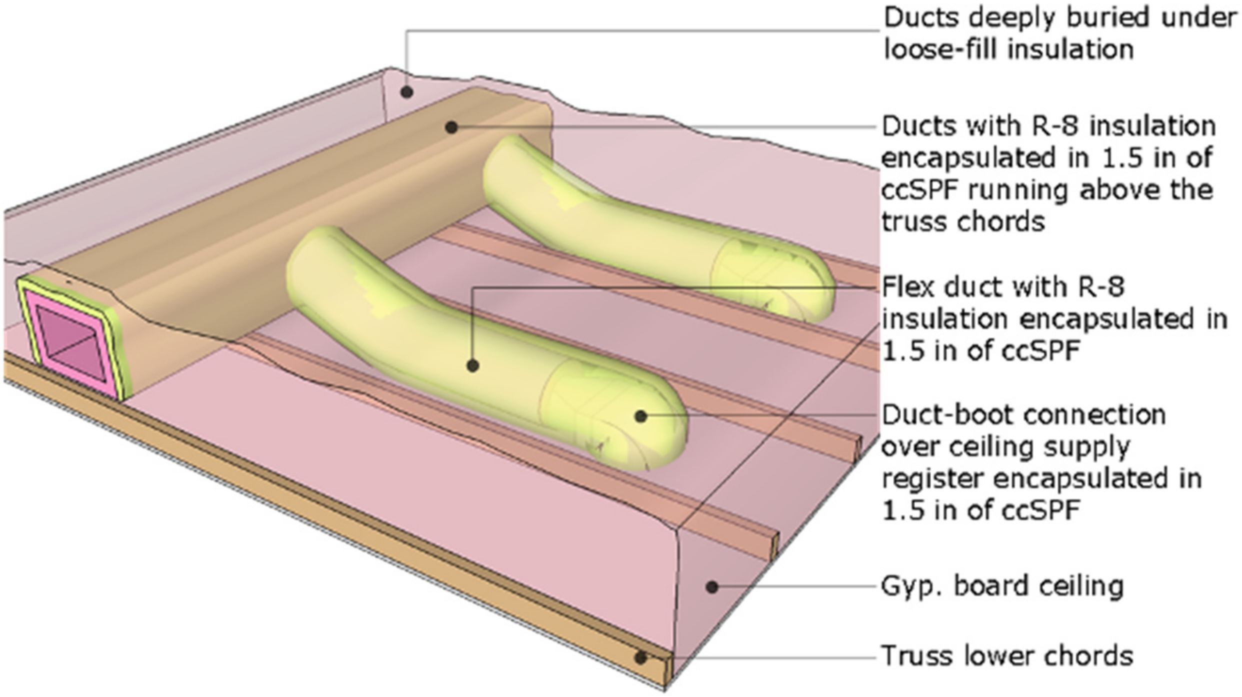


Figure 7. Diagram of BEDs

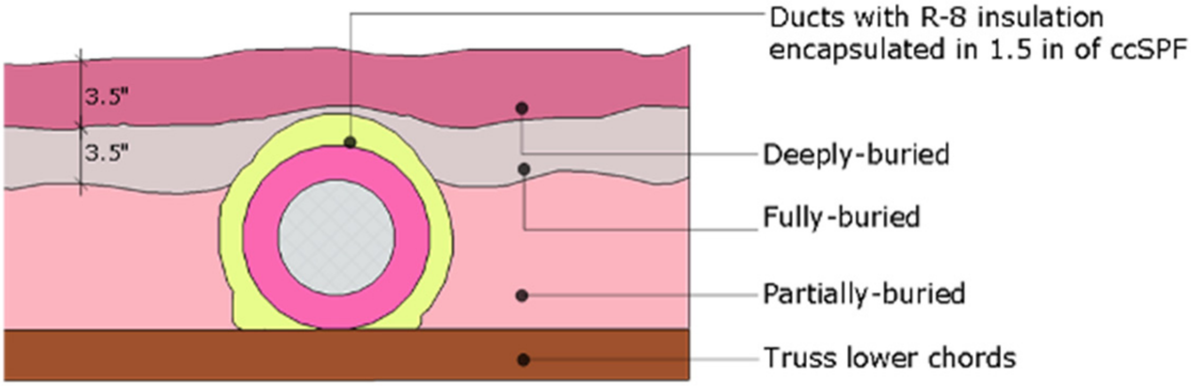


Figure 8. Categorization of BED insulation levels

Insulation Materials

Four insulation products are typically involved in BEDs installations: loose-fill fiberglass, loose-fill cellulose, ccSPF, and fiberglass duct wrap.

Loose-Fill Fiberglass

Loose-fill fiberglass insulation is composed of loosely packed rows of glass fibers. Large bales of fiberglass are torn apart and blown through a hose onto the attic ceiling assembly (Krigger and Dorsi 2004). R-values for this insulation are 2.2–2.9/in. (ASHRAE 2009).

Loose-Fill Cellulose

Loose-fill cellulose insulation is composed of newspaper and other wood waste treated with fire retardants (Krigger and Dorsi 2004). R-values for this insulation are 3.2–3.7/in.

Closed-Cell Spray Polyurethane Foam

ccSPF, also known as medium-density foam, has R-values of 6–7/in., qualifies as a class II vapor retarder at 1.5 in., and has excellent air sealing characteristics (Krigger and Dorsi 2004).

2.4 Code Compliance

While there are no significant obstacles to ensuring that buried duct installations are code compliant, installations involving ccSPF must be carefully considered. In general, the 2009 IRC requires that spray foam insulation applied to the exterior of ductwork (Sections M1601.3 and M1601.4) in attics (Section R316.5.3) meet several requirements:

- The spray foam has a flame spread index no greater than 50 and a smoke developed index no greater than 450.
- Attic access is required by Section R807.1 (typically required in low-density residential construction).
- The attic is "entered only for purposes of repairs or maintenance" (meaning no storage or habitation is allowed).
- The spray foam is protected by an ignition barrier.
- The spray foam has a maximum water vapor permeance of 3 perm/in. (meaning that open cell spray foam cannot be used).
- The spray foam meets the general requirements for use in residential buildings (Section R316).

The 2009 IRC allows exposed installations of ccSPF in attics, but the spray foam used must be specifically approved for installation without an ignition barrier

Fiberglass Duct Insulation

Most sheet metal ducts are uninsulated or wrapped on the outside with fiberglass insulation blankets, sometimes called "duct wrap" (Figure 9). These sheets (typically 2–4 ft wide) are 1–4 in. thick and include a vapor barrier on the outside—often with a foil radiant barrier. The R-value of fiberglass duct wrap is 2.5–4 h-°F- ft^2/Btu-in., depending on the specific product and density. Newer sheet metal ducts that have interior, insulating duct liners are now available, but these liners are not generally appropriate for retrofit applications (Aldrich and Puttagunta 2011).

Figure 9. Duct wrap

(Section R316.6). Approval is determined on the basis of specific fire-related test procedures. Not all ccSPF materials meet the requirements of Section R316.6.

If the spray foam used is not approved for exposed attic installations, encapsulated ducts must also be buried in loose-fill insulation such that the ccSPF is covered by an ignition barrier. For BEDs, 1.5 in. of fiberglass, which is considered mineral fiber insulation (ASTM C554-11), meets the minimum requirements for ignition barriers. BEDs using a ccSPF material specifically approved under Section R316.6 may be buried under cellulose. All other BED installations require 1.5 in. of fiberglass or mineral wool insulation coverage.

2.5 Effective R-Values

The thermal resistance of duct insulation products is typically listed as a nominal R-value that does not account for convective heat transfer and the geometry of the duct system (Palmiter and Kruse 2006). Effective R-values, on the other hand, account for these effects and are therefore a more precise measure of the amount of energy that is transferred between the ducts and the unconditioned space. For low R-values, the difference between the nominal and effective R-values is generally negligible, but for larger duct insulation values, effective R-values can be considerably smaller than the nominal ratings.

Unlike traditional duct insulation, buried ducts cannot be described using nominal R-values, and effective R-values must be simulated using computer models (Griffiths et al. 2004; Griffiths and Zuluaga 2004; Zoeller 2009; Shapiro et al. 2012). To provide an apples-to-apples comparison of the various duct insulation methods, effective R-values for an 8 in. flex duct are shown in Table 1. Other duct sizes will have different effective R-values, and in general, effective R-value increases with increasing diameter. (See Appendix B for detailed tables showing effective R-values for a wider array of insulation strategies and duct sizes.)

In Detail: Modeling Buried Duct Effective R-values

The heat transfer between the air inside buried ducts and the attic can be calculated using finite element computer modeling programs, such as THERM. The complicated geometry, lack of symmetry, and complex heat flow of buried ducts make direct calculation of effective R-values difficult. Unlike typical hung ductwork, buried ducts involve heat flow between three air spaces: the living space below the ceiling, the conditioned air inside the duct, and the attic air. Heat flows between these areas simultaneously, and the degree of heat flow changes based on the conditions of each area. To find the effective R-value, which is the R-value of a hung duct with the same performance, the heat flow between the duct and the attic must be isolated.

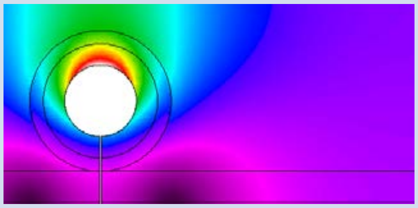


Figure 10. Heat flux magnitude through buried and encapsulated duct. Red and yellow show greatest flux.

Table 1. Summary of Effective R-Values for an 8-in. Duct

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 Beneath Fiberglass	8.1	10.2	12.3
Fully Buried Beneath Fiberglass	12.0	14.1	16.2
Deeply Buried Beneath Fiberglass	20.7	22.1	23.5
Encapsulated (1.5 in.) and Partially Buried Beneath Fiberglass	18.4	19.7	21.0
Encapsulated (1.5 in.) and Fully Buried Beneath Fiberglass	22.6	23.8	25.0
Encapsulated (1.5 in.) and Deeply Buried Beneath Fiberglass	29.6	30.3	31.1

Source: Shapiro et al. (2012)

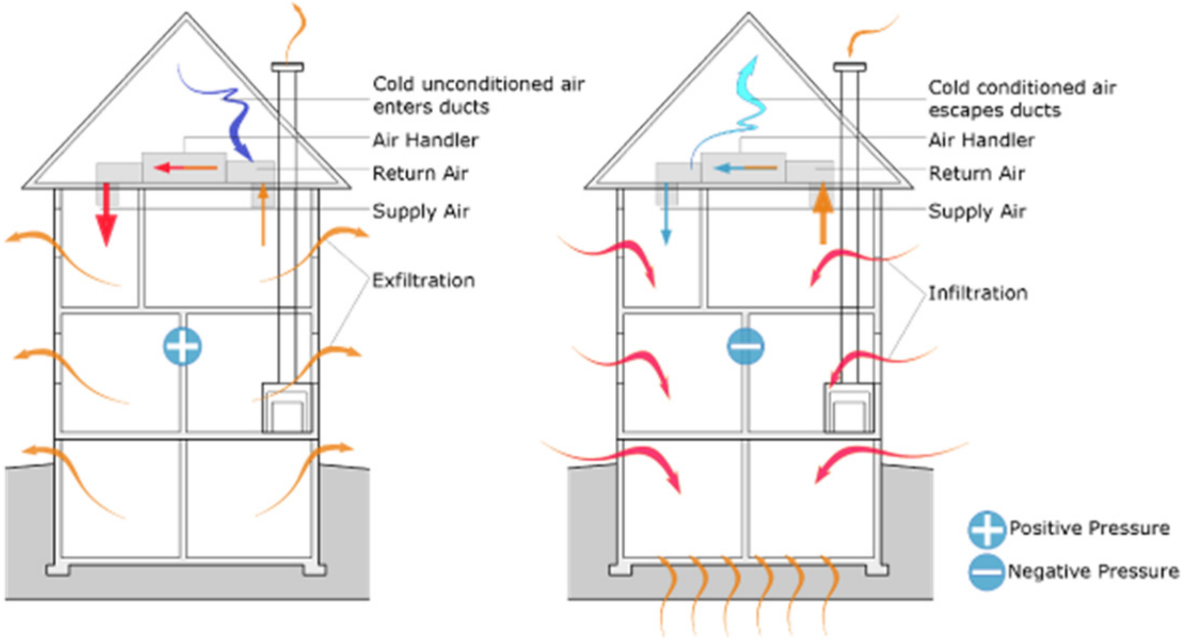
2.6 System Interactions

The energy savings associated with BEDs depend heavily on the space-conditioning system installed in the house. Counterintuitively, BEDs may reduce space-conditioning energy use by a larger percentage when a multispeed or right-sized air-conditioning system is installed. These systems operate at lower capacities for longer periods of time than conventional systems, and thermal losses from ductwork therefore account for a larger percentage of the total load (Beal et al. 2011). For example, a recent study found that switching from an attic duct system to an indoor duct system reduced cooling energy use by 17.3% for a multispeed seasonal energy efficiency ratio 21 system but only reduced cooling energy use by 11.2% for a single-speed seasonal energy efficiency ratio 13 system. The experiment was conducted by alternating the use of these systems in a 1,600-ft^2 laboratory test house in Florida (Cummings and Withers 2011).

BEDs will reduce the heating and cooling loads of the building, and as a result, the space-conditioning systems may be downsized in some cases. In new construction, equipment downsizing will reduce the cost of implementing a BED strategy. In retrofit scenarios, the energy savings and cost of a BED strategy will depend on whether a new, downsized space-conditioning system is installed. If the space-conditioning system is not downsized, the reduction in load associated with BEDs may increase cycling in the space-conditioning equipment, reducing the efficiency of the equipment and energy savings. Alternatively, simultaneous replacement of space-conditioning equipment and implementation of a BEDs strategy may be a way to reduce installation costs and maximize energy savings.

Ducts installed in unconditioned attics can also cause comfort issues for the occupants. When the space-conditioning system is not running, the air inside the ductwork can be heated or cooled substantially, depending on the season. When the system begins operation, this hot or cold air is pushed into the conditioned space, increasing the space-conditioning load and causing comfort problems for the occupants. By increasing the R-value of the ductwork and reducing air losses, BEDs can dramatically reduce these effects.

Furthermore, leakage from the duct system can depressurize or pressurize the conditioned space, which leads to increased envelope air infiltration and a greater potential for moisture problems. Return-side leakage can create positive pressure in the home and result in unconditioned air and pollutants being pulled into the airstream. Positive pressure can be an issue during winter months in cold climate regions if relatively moist interior air is pushed into the wall assembly and condenses. Similarly, attic supply side leakage can create negative pressure in the home and result in conditioned air being lost to the outdoors. If there are atmospheric combustion appliances in the home, negative pressures can interfere with proper drafting, potentially resulting in exhaust gases building up within the home. In hot, humid climate regions, depressurization can also lead to high indoor relative humidity levels as outdoor air infiltration is exacerbated (Aldrich and Puttagunta 2011). Encapsulating ducts can reduce leakage; in addition to substantial energy savings, lower duct leakage can alleviate moisture, comfort, and safety concerns.



Return Side Leakage (Winter) **Supply Side Leakage (Summer)**

Source: Aldrich and Puttagunta (2011)

Figure 11. How duct leakage can affect building pressures

3 Decision-Making Criteria

While each combination of building construction, ductwork installation, and space-conditioning system poses unique challenges to reducing ductwork thermal losses, there is fortunately a wide array of solutions that may meet the challenges of each building. Broadly speaking, there are three major categories for reducing ductwork thermal losses: (1) proper duct sealing and insulation; (2) placing ducts within the thermal envelope; and (3) burying and/or encapsulating ducts in unconditioned attics. Under each duct installation category are multiple implementation options, and each option must be carefully considered based on the tradeoffs in cost, energy savings, and practicality of each building installation.

Proper duct sealing and insulation are applicable to the widest array of system types, but ductwork thermal losses can only be reduced to around 10% of total space-conditioning loads through duct sealing and insulation alone (Shapiro et al. 2012). Furthermore, proper duct sealing and insulation may not be practical in all existing buildings without major reconfiguration of the duct system. Various duct sealing and insulation methods may be employed for different system types; see the BA Measure Guideline, *Sealing and Insulating Ducts in Existing Homes* (Aldrich and Puttagunta 2011) for more information.

To minimize or eliminate duct thermal losses, however, ducts within the thermal envelope or BEDs must be installed. Choosing the most appropriate method of reducing duct thermal losses can be a complicated endeavor that relies heavily on the building and space-conditioning systems. This guideline attempts to clarify this decision-making process by providing guidance on which methods may be appropriate for specific circumstances. First, this guideline provides a summary of the advantages, disadvantages, and specific risks associated with each of the measures in order to provide guidance on which measures may not be applicable for the installation. Second, cost and performance metrics are provided to allow homeowners and contractors to select the best of the remaining options that fit the desired performance needs.

3.1 Advantages, Disadvantages, and Risk Identification

Each of the options available for minimizing or eliminating ductwork thermal losses has advantages, disadvantages, and risks that will affect the decision-making process. The sections below give detailed descriptions of the various methods of reducing ductwork thermal losses, including the four major methods of placing ducts within the thermal envelope and the BED strategies. Table 2 summarizes which options are available for each building construction type. The table shows yes or no values based on building age (new or existing) and climate region (dry or humid). For the purposes of this guideline, humid climates are all moist and marine climate zones as classified by the International Energy Conservation Code (IECC). This classification is discussed in greater detail in Section 4.1.

Table 2. Applicability Decision Table
(Green Dots = Yes; Red Dots = No)

	New Construction		Existing Buildings	
Climate	**Humid**	**Dry**	**Humid**	**Dry**
Unvented attic	✓	✓	✓	✓
Furred-down chase	✓	✓	✗	✗
Furred-up chase	✓	✓	✗	✗
Encapsulated ducts[a]	✗	✗	✓	✓
Buried ducts	✗	✓	✗	✓
Buried & encapsulated ducts	✓	✓	✓	✓

[a] **Encapsulated ducts can be installed safely in new construction, but it is better to bury and encapsulate**

3.1.1 Ducts Within the Thermal Envelope

With proper planning and careful attention to detail, the thermal losses associated with ductwork can be eliminated by placing ducts within the thermal envelope using one of four methods: (1) expanding the thermal envelope to incorporate ductwork (e.g., insulating attics at the roof deck

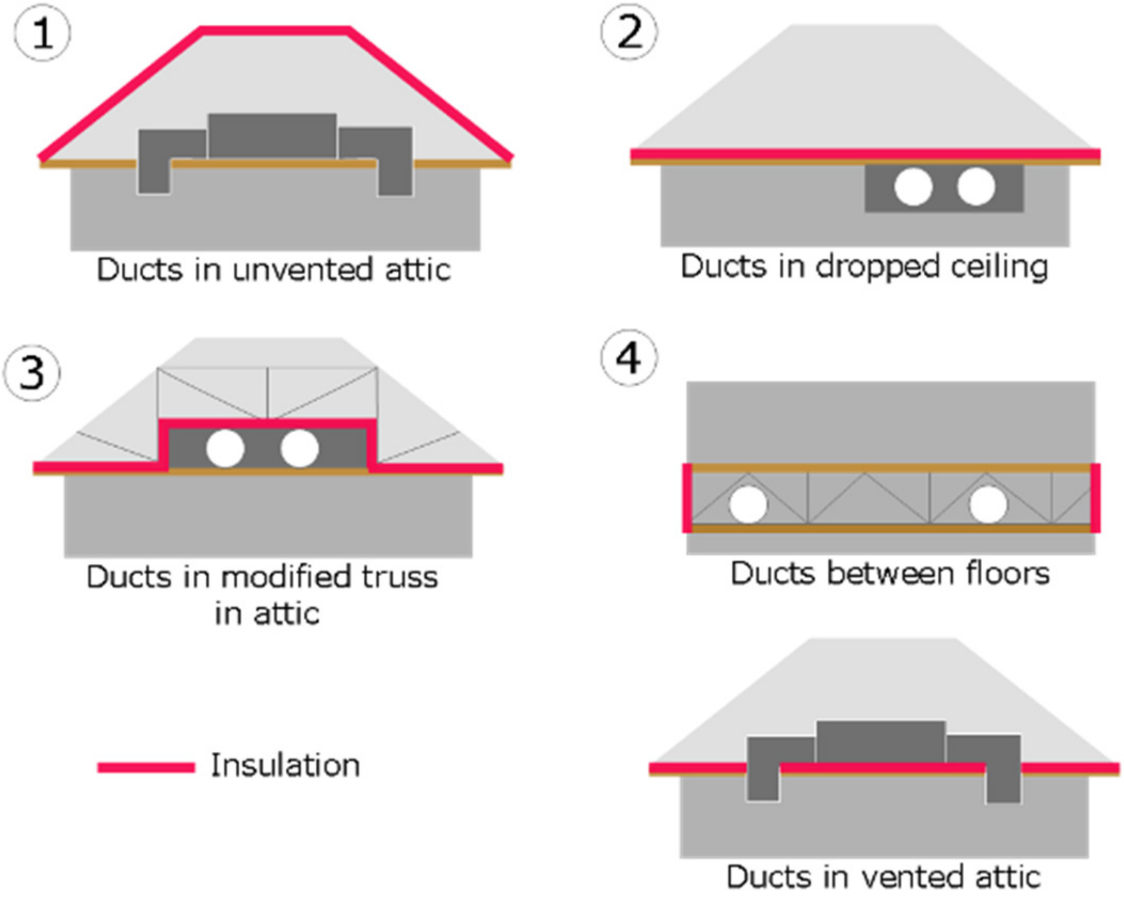


Figure 12. Interior duct insulation options

and insulating basements at the basement walls); (2) installing ductwork in a soffit or dropped ceiling; (3) using a modified truss to create an insulated space within the thermal envelope for ductwork in the attic; and (4) installing ductwork between floors (CARB 2000; Hendrick 2003; Roberts and Winkler 2010; Beal et al. 2011). (See Figure 12 for a diagram showing these methods.) Methods (2) through (4) are the most effective of the interior duct strategies. While method (1), expanding the thermal envelope to include ductwork, eliminates ductwork thermal losses, the expanded enclosure surface area can result in increased space-conditioning loads. Although the increased space-conditioning loads can be smaller than the eliminated ductwork losses, the resulting savings from this method may be less than the other methods.

3.1.1.1 Unvented (Cathedralized) Attics

Moving the thermal boundary to the roof deck creates an added interior volume for placing ducts within the thermal envelope. By taking this approach, the surface area of the thermal envelope is also increased, which results in increased space-conditioning loads from the enlarged enclosure (Hendrick 2003). While this penalty may be overcome by savings from ductwork thermal losses, the net energy savings (duct savings minus increased enclosure loads) may be less than savings from other methods of placing ducts within the thermal envelope.

Furthermore, by placing all the bulk water, water vapor, and thermal control boundaries within the same assembly, very different moisture control dynamics are created at the roof deck. The properties of the various materials used and how they are assembled must be clearly understood by the designer. Building codes require minimum levels of air-impermeable insulation for condensation control (Table 3), and insulation must be installed such that it does not become dislodged from the roof deck assembly. As a result, spray foam is typically used to insulate buildings at the roof deck. Achieving the equivalent R-value at the roof deck using spray foam is significantly more expensive than installing loose-fill insulation along the ceiling plane. The larger surface areas of the roof deck and vertical gable walls, if present, result in higher costs compared to ceiling insulation, and spray foam is comparatively more expensive than loose-fill insulation per achieved R-value. Insulating the building at the roof deck using spray foam, however, provides greater air sealing benefits than typical ceiling insulation methods. Rigid insulation may be placed on top of the roof deck, removing the need for ccSPF insulation except at the soffits, and as a result, unvented attic construction may be less expensive in new construction or at the end of an existing roof’s service life than in most retrofit situations.

Table 3. Insulation for Condensation Control

Climate Zone	Minimum Air-Impermeable Insulation R-Value
2B and 3B with tile roof	None
1, 2A, 2B, 3A, 3B, and 3C	R-5
4C	R-10
4A, 4B	R-15
5	R-20
6	R-25
7	R-30
8	R-35

Source: IRC Table R806.4

3.1.1.2 Ducts in Dropped Ceilings or Internal Soffits (Furred-Down Chase)

A furred-down chase is essentially a dropped ceiling or internal soffit strategically placed to carry ductwork through the home. Furred-down chases require planning and architectural coordination on the part of the building designer to ensure that the dropped ceiling can be placed in an inconspicuous location, such as a hallway or tray ceiling, and still allow the ducts to reach all the required register locations. Ductwork must be carefully planned and sized to fit inside the furred-down chase. Large spaces may be particularly difficult to serve using this method because register throw distances are limited. Except in modest floor plans, compact distribution may be difficult to achieve. Coordination between trades is also further complicated during the implementation phase (Hendrick 2003; Beal et al. 2011). This method may be very difficult to implement in existing homes.

3.1.1.3 Ducts in Modified Truss (Furred-Up Chase)

A furred-up chase is similar to a furred-down chase, except a contained volume for the ductwork is created above the ceiling plane in the attic. This method typically uses a modified truss system to create an insulated space within the thermal envelope for the ductwork. A squared-off plenum truss or a modified scissors truss can be used to create space for the duct distribution system. Like the furred-down chase described above, the dedicated duct space must be carefully air sealed and thermally separated from the attic space. A variety of materials can be used as the air barrier, including gypsum board, laminated fiber sheathing, and oriented strand board. This strategy tends to work best for compact floor plans where the insulated space can be correspondingly compact. As with the previous two methods, this method is typically not practical for existing homes.

3.1.1.4 Ducts Between Floors

In multistory buildings, ducts can be placed within the floor framing cavity between levels. This can be an ideal solution, but design coordination between the structure, floor plan, and duct layout is critical for success. The concept works best when utilizing open-web floor trusses rather than I-joists or sawn lumber joists. This method works well in heating climates where floor registers are acceptable for HVAC distribution, but in cooling climates, where ceiling or high-wall registers are more effective, additional design and coordination solutions are required. Vertical branches serving high wall registers work well, but serving both floor levels through one set of ducts in the shared floor cavity can be challenging. If the home has a basement, ducts may be placed in both floor cavities, simplifying the design and installation. This method is not viable for existing homes.

3.1.2 Buried and Encapsulated Ducts

BEDs have advantages in performance, first cost, and flexibility of application relative to other ductwork improvements. From a performance perspective, BEDs can approach the efficiency of true inside-conditioned-space ducts and, in some cases, exceed the performance of ductwork placed in unvented attic assemblies. Combining best practices in duct sealing, low-profile and compact duct design, and deeply buried ducts will result in a very efficient distribution system Assuming planning and design costs are held constant, the only additional cost directly attributable to a BEDs solution for new construction is the ccSPF application. Although some attics may not be conducive for this strategy, buried ducts—which do not require ccSPF encapsulation—are essentially a zero-cost energy efficiency measure with a slight performance tradeoff over true inside-conditioned-space duct systems.

Furthermore, BED strategies are highly flexible, allowing for use in most vented truss roof scenarios. Depending on construction sequencing, buried (and encapsulated)[1] ducts can be installed either before or after ceiling drywall. Compact HVAC design, which is a preferred method of reducing ductwork thermal losses and improving space-conditioning system efficiency, can be accommodated in BED applications. As codes push the required ceiling insulation to higher R-values, the performance of buried (and encapsulated) ducts will improve; i.e., ducts can be buried to a greater extent.

The most significant risks for BED applications are air leakage into the vented attic—with all the corresponding pressure balance and indoor air quality concerns—and condensation potential on the buried duct surfaces during cooling operation. These risks are essentially quality control and design issues that require contractor training and execution quality assurance to mitigate potential problems. Proper duct sealing using industry established best practices will reliably prevent air leakage, and following proper protocols for encapsulating buried ducts in adequate levels of ccSPF will prevent condensation on the surface of the ductwork.

To ensure that there are no condensation issues with buried ducts, ducts should not be buried without ccSPF encapsulation in moist and marine climates. For BED solutions, moist and marine climates correspond to IECC climate zones 1A, 2A, 3A, 4A, 4C, and 5A, with limited application in 6A and 7A (Figure 15). In humid climates, refer to the buried and encapsulated ducts sections. In dry climates, ducts can be insulation buried without the condensation control layer provided by ccSPF.

Where structural or other obstructions exist in the attic space, a third method—encapsulated (but unburied) ducts—may be employed. (See Section 2.2 for a detailed description.) This application subset is useful in new construction where complete burial of a short length of duct is not possible. In retrofits, encapsulated ducts may be used when a more comprehensive reworking of the existing ducts is impractical. Since the ignition barrier provided through mineral fiber insulation is eliminated in this configuration, ccSPF specifically rated for attic exposure or an alternative ignition barrier is required.

Although research has found that the BED strategies are not difficult to implement in new construction, BEDs are not common practice and require modifications to standard installation techniques (Griffiths et al. 2004; Griffiths and Zuluaga 2004; Zoeller 2009; Shapiro et al. 2012). Proper execution relies on initial planning, good communication, and coordination between the HVAC contractor and the project manager responsible for quality control. Training and detailed specifications will help to communicate project goals to all stakeholders.

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[1] Buried (and encapsulated) means buried or buried and encapsulated.

Proper HVAC equipment sizing and duct design will enable the use of smaller duct diameters and a more compact duct layout, both of which facilitate burying the ducts below an optimal level of insulation. An optimized insulation-buried duct HVAC system design includes:

- Properly sized air handling equipment, including downsized equipment based on the reduced thermal losses, when applicable
- Air handling equipment installed within the thermal envelope will also reduce the impacts of duct leakage
- Properly sized duct runs kept as short as possible to facilitate insulation coverage.
- Ductwork placed as low as practical and not hung from the trusses
- Minimized duct cross-overs that result in lower insulation coverage levels
- Duct runs placed parallel to truss chords and framing, where possible, to allow greater burial
- Side-entry ceiling register boots, rather than of top-entry boots, that prevent vertical duct protrusions above loose-fill insulation at connection points.

Ducts run perpendicular to the trusses can be supported by the bottom chords, and ducts run in parallel can be supported by the ceiling drywall. Ducts are typically “roughed-in” before installation of gypsum board ceilings, however, leaving no support for ducts that are run low and parallel to the truss chords. In cases where ducts are installed prior to the ceiling, temporary straps can be used to support duct lengths installed parallel to the truss bottom cords.

3.2 Cost and Performance

Once the applicable duct thermal protection options have been determined based on the risk identification process, the next step is to select the option that meets the desired performance outcome cost effectively in a given circumstance. To compare potential performance outcomes, energy modeling is helpful. This guideline provides energy savings estimates for a sample 2,400-ft^2 house built to Building American (BA) Benchmark specifications in each climate zone. This building is then outfitted with buried ducts, encapsulated ducts, buried and encapsulated ducts, unvented attics, and ducts in the thermal envelope. Building energy simulations were performed in BEoptE+ 1.3.

Table 4 shows an example of this energy savings analysis. Each option in the table is listed in the rows, while the roof slope is shown in the columns. Energy savings over the benchmark are shown for each of the options. Table cells are colored based on their relative energy savings. The highest savings is shown in green, and the lowest savings is shown in red. The benchmark includes a well installed duct system with R-8 insulation in a vented attic. In this example the non-encapsulated buried ducts, shown in gray, are not simulated because they are not appropriate for this example humid climate. Data for other cities and climate zones, as well as the modeling assumptions used, are provided in Appendix C.

Table 4. Percentage Total Source Energy Savings by Roof Slope (Atlanta, Georgia)[2]

	Roof slope			
Assembly (Attic R-value)	**4:12**	**6:12**	**8:12**	**10:12**
Benchmark (R-30)[a]	0.0%	0.0%	0.0%	0.0%
Improved benchmark (R-30)[a,b]	7.6%	7.6%	7.6%	7.7%
Partially-buried (R-33)	N/A	N/A	N/A	N/A
Fully-buried (R-42)	N/A	N/A	N/A	N/A
Deeply-buried (R-51)	N/A	N/A	N/A	N/A
Unvented (R-30)[a]	10.6%	10.3%	9.9%	9.5%
Encapsulated (R-30)[a]	9.1%	9.2%	9.2%	9.2%
Partially-buried & encapsulated (R-37)	11.1%	11.1%	11.1%	11.1%
Fully-buried & encapsulated (R-46)	12.1%	12.3%	12.2%	12.2%
Deeply-buried & encapsulated (R-54)	12.9%	13.1%	13.0%	13.0%
Interior ducts (R-30)[a]	11.9%	11.9%	11.9%	11.9%

[a] Benchmark ceiling or roof deck insulation is R-30 in Zone 3A. Ceiling insulation R-values for buried ducts may be higher than the benchmark.

[b] Improved Benchmark includes IECC 2012 requirements for infiltration (3 ACH_{50}) and duct sealing (4 cfm per 100 ft^2 conditioned living space).

In general, BEDs are similar in performance to interior ducts and ducts in unvented attics. The added ceiling insulation caused by encapsulating and deeply burying ducts outweighs the added benefit of interior ducts. BEDs become more effective than unvented attics as the roof pitch becomes higher because unvented attics have increased envelope loads as a result of the increased enclosure surface area.

Cost estimates for installations in Climate Zones 1, 2, and 3 are shown in Table 5 and were derived from three sources (Beal et al. 2011; RSMeans 2011; NREL 2012). These estimates are for new construction and include the insulation cost of the attic/roof assembly and ductwork. This table assumes that unvented attics are insulated entirely with ccSPF. Other construction methods are available for unvented attic assemblies, but outlining all of these methods is outside the scope of this guideline. Using ccSPF is probably the most common method of constructing unvented attics and was therefore used in this example. Existing building costs will vary widely based on the conditions of the ductwork and the degree of reconfiguration necessary. Other climate zones have different insulation requirements for attic installations and vapor-impermeable insulation at the roof deck.

To demonstrate how these cost and energy savings predictions could be used in the decision making process, two examples are provided. These examples cover humid and dry climates, and use the same models used for Appendix C. For both cases, a roof slope of 6:12 is assumed. The best metric for measuring total lifetime cost is annualized energy related costs (AERC), as described by Polly et al. (2011), but simple payback period is also given for each measure. Assumptions for the cost analysis are given in Table 6 and Table 7.

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[2] Savings are color coded by savings potential (green = most energy savings; red = least energy savings). Data are based on the BA Benchmark home in Atlanta, Georgia (Zone 3A) and modeled in BEoptE+ 1.3.

Table 5. Example Cost for 2,400-ft^2 Single-Story House With 6:12 Gable Roof in Climate Zones 1, 2, or 3. Duct Surface Areas Based on BA Benchmark With Two Returns

	Partially Buried	Fully Buried	Deeply Buried	Unvented ccSPF	Encap-sulated	Partially Buried and Encap-sulated	Fully Buried and Encap-sulated	Deeply Buried and Encap-sulated	Interior Ducts
R-30 ccSPF Roof Deck[a]				$8,363					
Encapsulated ducts[a,b]					$1,678	$1,678	$1,678	$1,678	
Partially Buried (R-33 Fiberglass)[c]	$95								
Fully Buried (R-42 Fiberglass)[c]		$380							
Deeply Buried (R-51 Fiberglass)[c]			$665						
Partially Buried and Encapsulated (R-37 Fiberglass)[c]						$222			
Fully Buried and Encapsulated (R-46 Fiberglass)[c]							$507		
Deeply Buried and Encapsulated (R-54 Fiberglass)[c]								$760	
Interior Ducts[d]									$1,680
Total Cost	**$95**	**$380**	**$665**	**$8,363**	**$1,678**	**$1,900**	**$2,185**	**$2,439**	**$1,680**

[a] Costs from RSMeans Residential Cost Data (RSMeans 2011).

[b] BA Benchmark assumes 888 ft^2 of ductwork. Actual ductwork surface area ranged from 218 ft^2 to 681 ft^2 for the three homes monitored by Shapiro et al. (2012). Costs for installations may be significantly lower than the cost cited here.

[c] Costs from the National Residential Efficiency Measures Database (NREL 2012).

[d] Cost from Beal et al. (2011).

Table 6. Cost Analysis Assumptions

Cost Metric	Assumption
Analysis Period	30 years[a]
Measure Lifetimes	30 years[b]
Inflation Rate	3%[a]
Real Discount Rate	3%[a]
Real Fuel Escalation Rate	0%[a]
Mortgage Rate	4.42%[c]
Mortgage Period	30 years[c]
Marginal Income Tax Rate	28%[a]

[a] BEopt defaults (NREL 2012)
[b] All building components given the same lifetime for simplicity
[c] Average rate for 2011 (Freddie Mac 2012)

Table 7. Fuel Prices and Characteristics for Energy and Cost Analysis

Energy Source	Site to Source Ratio[a]	Cost[b]	Energy Content
Electricity	3.365	$0.1172/kWh	3,412 Btu/kWh
Natural Gas	1.092	$1.10/therm	100,000 Btu/therm

[a] Deru and Torcellini (2007)
[b] Prices obtained from EIA (2012a, 2012b). Electricity and natural gas prices represent average national prices for 2011.

3.2.1 *Dry Climate Decision-Making Example: Las Vegas, Nevada*

To demonstrate how the savings and cost data would be used to choose the best duct and attic insulation option in the dry climate of Las Vegas, Nevada, the cost data provided Table 5 and the modeled building energy savings provided in Table 20 are used. Source energy savings and AERC compared to the improved benchmark are plotted in Figure 13. Deeply buried and encapsulated ducts have the highest energy savings, interior ducts have the highest energy savings without increasing costs over the improved benchmark, and deeply buried ducts are the lowest cost option. Noticeably, unvented attics installed with ccSPF have the highest cost of all the measures. Unsurprisingly, simple payback paints a similar picture (Table 12).

Table 8. Cost Analysis for Las Vegas Home Compared to Improved Benchmark

Assembly (Attic Insulation)	AERC ($/yr)	Source Energy Savings (%)	Simple Payback (yr)
Partially Buried (R-33)	–16	1.7	4.9
Fully Buried (R-42)	–28	3.5	9.2
Deeply Buried (R-51)	–35	5	11.4
Unvented (R-30)	258	2.8	256.8
Encapsulated (R-30)	35	2	71.5
Partially Buried and Encapsulated (R-37)	18	4.1	39.3
Fully Buried and Encapsulated (R-46)	12	5.5	34.1
Deeply Buried and Encapsulated (R-54)	9	6.5	32.2
Interior Ducts (R-30)	–2	5.2	27.6

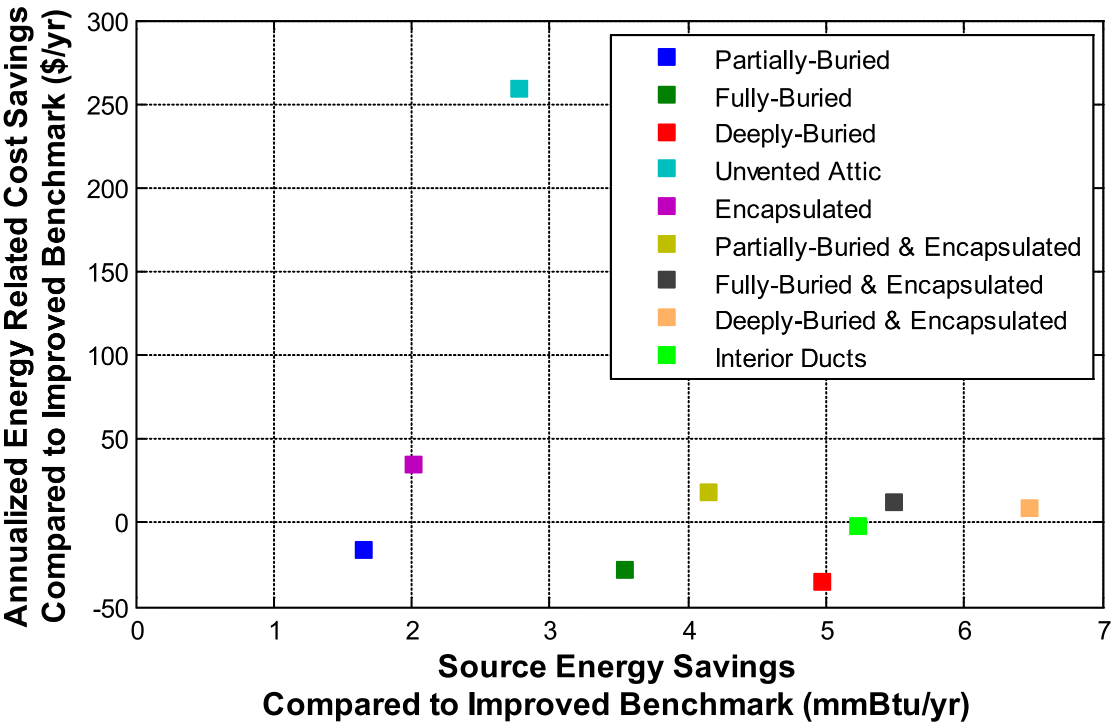


Figure 13. AERC versus source energy savings compared to improved benchmark for Las Vegas

3.2.2 Humid Climate Decision-Making Example: Atlanta, Georgia

A similar methodology was employed for the house placed in Atlanta, Georgia. The only difference, however, is that buried ducts without encapsulation were not considered because there is a risk of condensation of the surface of the ductwork. Costs are listed in Table 5 and energy modeling results are given in Table 4. As with Las Vegas, deeply buried and encapsulated ducts have the highest energy savings. Fully buried and encapsulated ducts have the highest energy savings without increasing costs over the improved benchmark, and interior ducts are the lowest cost option. Noticeably, unvented attics installed with ccSPF have the highest cost of all the measures. Unsurprisingly, simple payback paints a similar picture (Table 12).

Table 9. Cost Analysis for Las Vegas Home Compared to Improved Benchmark

Assembly (Attic Insulation)	AERC ($/yr)	Source Energy Savings (%)	Simple Payback (yr)
Unvented (R-30)	243	3	174.3
Encapsulated (R-30)	30	1.7	59.7
Partially Buried and Encapsulated (R-37)	4	3.8	30.8
Fully Buried and Encapsulated (R-46)	–6	5	26.6
Deeply Buried and Encapsulated (R-54)	–11	5.9	25.4
Interior Ducts (R-30)	–17	4.6	22.2

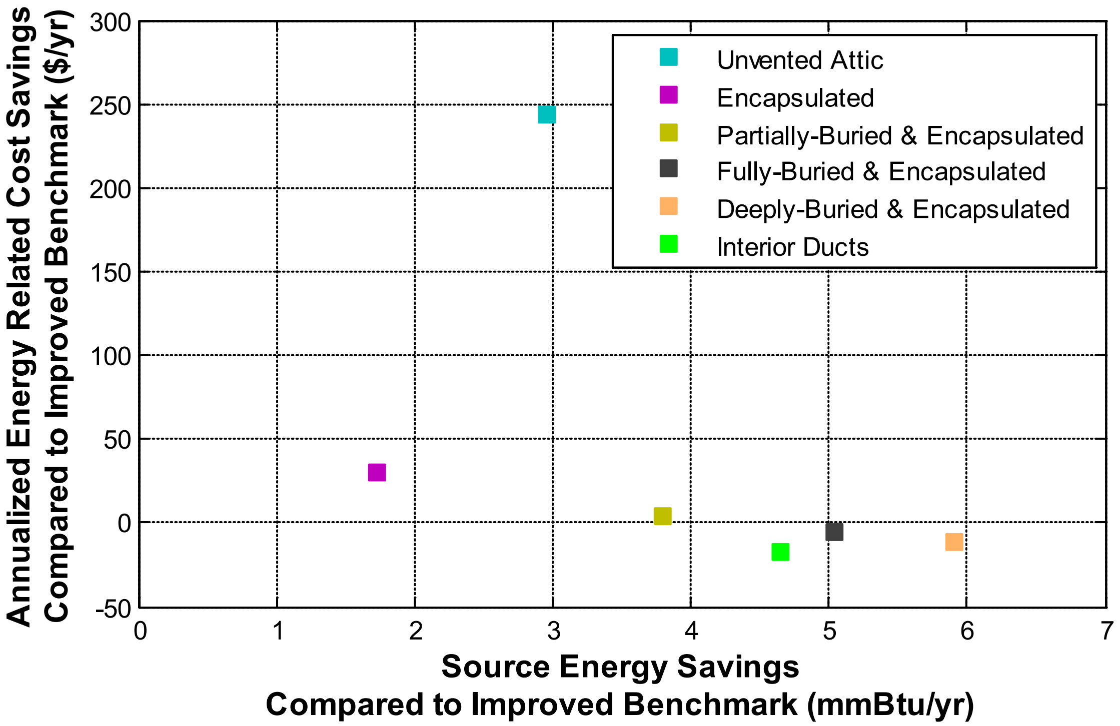


Figure 14. AERC versus source energy savings compared to improved benchmark for Atlanta

4 Measure Implementation

Scope of Work

1. Determine BED strategy to be employed.
2. Ensure work can proceed safely.
3. Survey conditions and create a duct installation or retrofit plan to accommodate BED design.
4. Test ductwork to ensure performance criteria are met.
5. Air seal ceiling plane penetrations.
6. Install BED strategy by burying ductwork beneath loose-fill insulation and/or encapsulating ductwork with ccSPF insulation.

Section 4.1 gives a discussion of climate specific factors impacting BEDs and the following sections give a detailed, step-by-step summary of the installation procedures for buried, encapsulated, and buried and encapsulated ducts in new and existing homes. Each set of instructions is accompanied by a diagram in Appendix A showing the proper installation procedure for the system. This guideline does not cover HVAC basics and duct design, both of which are covered in other comprehensive documents (ACCA 1992, 1995, 1997, 2006, 2007, 2009; Burdick 2011; Aldrich and Puttagunta 2011). Those engineering and design principles should be well understood by the designer and used as the starting point in designing and implementing a BED system. This guideline uses as its foundation the information contained in those and other HVAC duct design resources, and provides supplemental information useful in successfully designing and implementing the BED technique.

4.1 Climate-Specific Factors

The climate in which a project is located can impact the implementation of a BED strategy. First, there are interactions between IECC code requirements for attic insulation and duct burial level. Since attic insulation requirements increase with heating degree days, ducts can be buried to higher insulation levels without additional insulation over the IECC attic insulation requirements. For example, the minimum R-30 attic insulation requirement (Table 10) in climate zones 1–3 means that even achieving partial burial with loose-fill fiberglass insulation would require additional attic insulation in these climate zones (Table 11). In climate zones 6–8, however, the R-49 minimum required attic insulation requirement allows fully buried ducts to be installed without additional attic insulation.

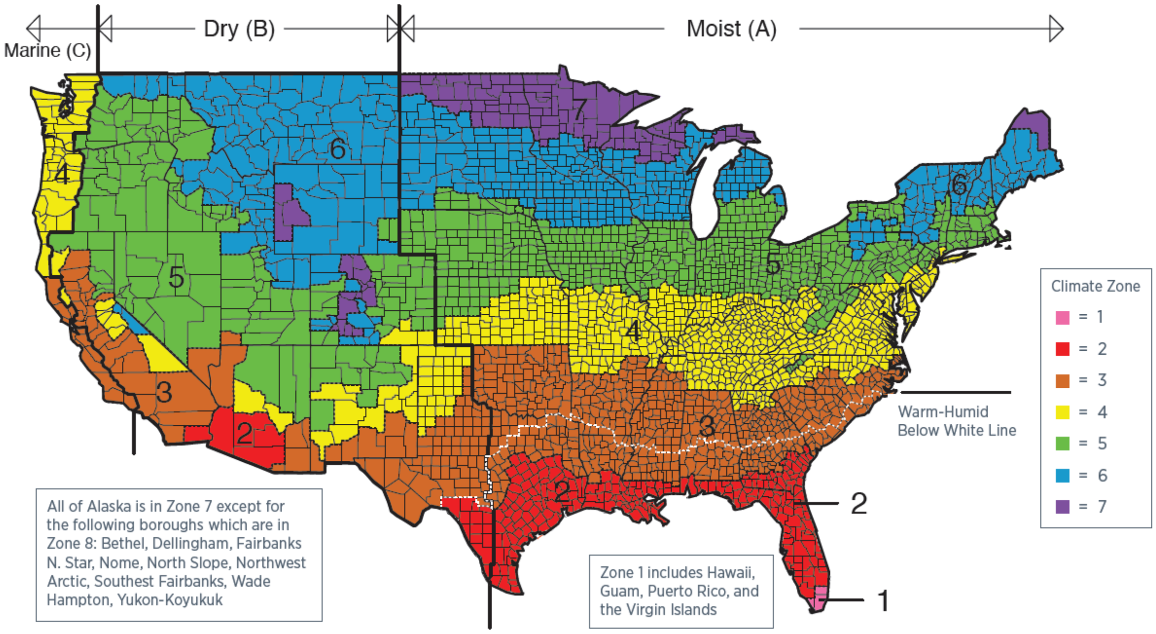
Table 10. Code Minimum Attic R-Values

Climate Zones	Minimum Attic R-Value
1, 2, and 3	30
4 and 5	38
6, 7, and 8	49

Table 11. Practical Achieved R-Value of Attic

Burial Level	Buried	Buried and Encapsulated
Partially	33	37
Fully	42	46
Deeply	51	54

As previously mentioned, ccSPF encapsulation is required in humid climates to reduce the risk of condensation on the outer surface of the duct jacket. As a result, (buried and) encapsulated ducts are recommended in all humid climates. In the United States, humid climates correspond to IECC climate zones 1A, 2A, 3A, 4A, 4C, and 5A, with limited application in 6A and 7A (Figure 15).



All of Alaska is in Zone 7 except for the following boroughs which are in Zone 8: Bethel, Dellingham, Fairbanks N. Star, Nome, North Slope, Northwest Arctic, Southest Fairbanks, Wade Hampton, Yukon-Koyukuk

Zone 1 includes Hawaii, Guam, Puerto Rico, and the Virgin Islands

Souce: Baechler et al. (2010)

Figure 15. IECC climate regions

When BEDs are used, the ducts must have at least 1.5 in. of ccSPF insulation encapsulating the entire surface of the ductwork. An encapsulation level of 1.5 in. was found to be appropriate for climate zone 2B by Shapiro et al. (2012). Since detailed analysis of all climate zones has not been performed, 1.5 in. of ccSPF is recommended for all climate zones as a conservative measure to prevent condensation. Ducts may be sealed to air-impermeable materials—such as gypsum board, extruded polystyrene (XPS) insulation, or polyisocyanurate insulation board—but not to air-permeable materials—such as fiberglass or cellulose insulation. Air-impermeable insulation is classified as having air permanence ≤ 0.02 L/s-m^2 at 75 Pa pressure (ICC 2009).

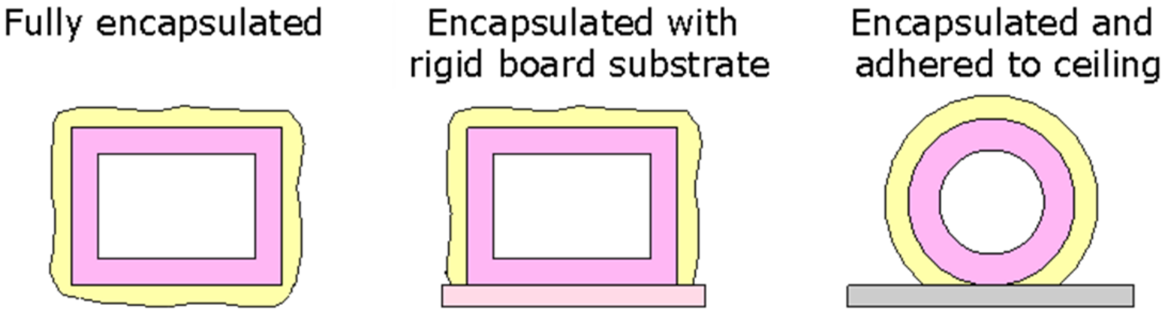


Figure 16. Methods of air sealing ductwork with spray foam to prevent condensation

4.2 Installation Procedures for Buried and Encapsulated Ducts in New Construction

BEDs in new construction have few impediments and are extremely flexible. As with all advanced systems, however, the key to optimal implementation lies with the initial planning. To accommodate a BED strategy, the designer must also consider how best to incorporate a low-profile design, where the system layout is specifically designed to place ducts as low as practical and allow ductwork to hug the drywall ceiling where possible. This guideline assumes other best practice measures, which assist in achieving the desired low-profile layout, will be incorporated into the building, including compact HVAC distribution and right-sized HVAC sizing. Specifically, smaller ducts (lower duct height) and inboard registers (shorter duct runs) mean that there is less ductwork to bury.

Typically, the duct design will consist of one or more main supply trunks and perpendicular duct branches serving each of the ceiling registers. If the trunk is perpendicular to the truss bottom chords, then the duct branches can be parallel and rest directly on the ceiling. If the main trunk is placed parallel to the ceiling supports, then the branches will need to run perpendicular to and rest on top of the truss chords. Either configuration will work, giving the designer the flexibility to select whichever method works best for a particular circumstance. In every case, a compact, low-profile layout should be a primary goal.

Return trunks and branches could be treated in the same manner; however, to keep the HVAC distribution system at a minimum, while simultaneously providing good comfort and proper airflow, the use of central returns is recommended. Return air paths from bedrooms and other spaces can be accommodated by low-profile jump ducts. Because condensation is not a concern on return ducts, encapsulation is not required. However, encapsulation is an excellent air sealing strategy, and is therefore recommended on all ductwork.

When planning for BEDs installations in new construction, the following steps should be taken. This decision-making process should take into account the discussion in Section 3.1.

1. **Determine the BED method to be applied.** For new construction, the available options are buried ducts and BEDs, depending on the climate and level of performance desired. In moist and marine climates, BEDs should be employed.

2. **Design a compact, low-profile duct system.** Using industry-accepted best practices for the design of ducted heating and cooling air distribution systems, develop a duct design with the objective of keeping the height of the system as low as reasonably practical relative to the gypsum board ceiling. Taking into account the register locations for each room, the location of the AHU, and any structural impediments presented by framing, the designer should determine the size and placement of supply trunks and supply register branches. Although not essential, it is generally advantageous for the main supply trunk to run perpendicular to and on top of the ceiling framing, and for the branch runs to run parallel to the ceiling framing and directly on the ceiling. Utilizing a rectangular—rather than square or round—section for the main supply trunk or trunks helps keep the overall height low, especially if placed on top of the ceiling framing. The vertical dimension of the trunk cannot be smaller than the diameter of the largest branch duct to allow for proper duct connections. All branch connections should be side takeoffs, and all ceiling registers should utilize side-entry boots. Duct crossovers should be avoided.
3. **Determine the construction sequence to be employed.** Installing the ducts either prior to or after the ceiling gypsum board is compatible with BED installations. Installing the ceiling drywall first has the advantage of allowing the ducts to rest directly on the ceiling plane and therefore being approximately 1.5 in. lower than when foaming the ducts first. The ducts are also supported by the ceiling during rough-in, and the entire system, including ceiling register boots, gets secured into place and air sealed when the ccSPF is applied to the ducts. Installing the ceiling first may hamper the ability to inspect or access ducts at low spaces at the edge of the sloped roof. Typically, the mechanical rough-ins, which include ducts, are performed prior to drywall, and access to the attic space may be constricted by the ceiling being in place. Where circumstances allow, however, installing the ceiling first provides additional benefits worth considering.
4. **Determine the depth of duct burial.** Based on the height of the duct branches and supply trunks relative to the ceiling plane and the depth of the loose fill insulation intended, determine the depth and category of duct burial. If needed, redesign the ducts or specify increased insulation depth to achieve the degree of burial desired. Remember, if the ducts are to be ccSPF encapsulated, some foams require a 1.5-in. minimum mineral fiber covering for a code required ignition barrier. Refer to 2009 IRC 316.5.3 for specific requirements.

4.2.1 Buried Ducts Installed After Ceiling (Dry Climate Only)

Buried ducts may be installed before or after the ceiling is installed. This step-by-step installation detail explains how to install buried ducts if the ceiling is installed before the ductwork is installed. This procedure does not require supporting ductwork before the ceiling is installed, but ductwork installation may be more difficult in this case.

1. 

Install ceiling gypsum board prior to installing buried ducts.

2. 

Install ductwork with a minimum of R-8 duct insulation in accordance with low-profile duct design.

3. 

Mastic seal all connections, and pull insulation jackets fully over joints and connections following best practice duct sealing strategies. Tool-tightened tension ties must be applied to the inner and outer liners.

4. 

Test total duct leakage to ensure performance levels are met (total duct leakage $\leq$ 3 $\text{cfm}_{25}/100\ \text{ft}^2$ of conditioned space).

5.

Air seal ceiling plane penetrations, including sealing duct register boots to gypsum board ceiling. Spray foam provides the best sealing benefits for this application.

6.

Install loose-fill insulation to specified depth, and verify that the ducts are covered to the level of design intent. Either loose-fill cellulose or fiberglass insulation may be used.

4.2.2 Buried Ducts Installed Before Ceiling (Dry Climate Only)

This step-by-step installation detail explains how to install buried ducts if the ceiling is installed after the ductwork is installed. This method is similar to the method described in Section 4.2.1, but requires supporting the ductwork before the ceiling is installed. Temporary strapping must be removed before burial.

1.

Install ductwork with a minimum of R-8 duct insulation in accordance with low-profile duct design**.** Where ducts are running parallel to ceiling framing, provide temporary strap supports to hang ducts at approximate ceiling plane level.

2.

Mastic seal all connections, and pull insulation jackets fully over joints and connections following best-practice duct sealing strategies**.** Tool-tightened tension ties must be applied to the inner and outer liners.

3. 

Test total duct leakage to ensure performance levels are met (total duct leakage ≤ 3 cfm_{25}/100 ft^2 of conditioned space).

4. 

Install ceiling gypsum board.

5. 

Air seal ceiling plane penetrations, including sealing duct register boots to gypsum board ceiling. Spray foam provides the best sealing benefits for this application**.**

6. 

Install loose-fill insulation to specified depth, and verify that the ducts are covered to the level of design intent. Either loose-fill cellulose or fiberglass insulation may be used.

4.2.3 Buried and Encapsulated Ducts Installed After Ceiling (Any Climate)

This step-by-step installation detail explains how to install BEDs if the ceiling is installed before the ductwork is installed. This procedure is similar to the method described in Section 4.2.1 for buried ducts with the same installation sequence, but includes the encapsulation process.

1.


Install ceiling gypsum board prior to installing buried ducts.

2.


Install ductwork with a minimum of R-8 duct insulation in accordance with low-profile duct design**.**

3.


Mastic seal all connections, and pull insulation jackets fully over joints and connections following best practice duct sealing strategies. Tool-tightened tension ties must be applied to the inner and outer liners**.**

4.


Test total duct leakage to ensure performance levels are met (total duct leakage ≤ 3 $cfm_{25}/100\ ft^2$ of conditioned space). Testing should be performed before encapsulation because it may be difficult to correct sealing issues after the application of spray foam.

5.


Apply at least 1.5 in. of ccSPF to all duct surfaces, including trunks, branches, and register boots. Where obstructions make the bottom of ducts inaccessible (such as when a wide trunk is placed on top of and perpendicular to the ceiling framing), ducts may be placed on 1.5-in. thick XPS or polyisocyanurate insulation board. Ducts should be entirely encapsulated and sealed to the gypsum board, or to rigid insulation board.

6.

Air seal ceiling plane penetrations, including sealing duct register boots to gypsum board ceiling. Spray foam provides the best sealing benefits for this application**.**

7.

Install loose-fill insulation to specified depth, and verify that the ducts are covered to the level of design intent. Fiberglass or other mineral fiber insulation must cover the ccSPF by at least 1.5 in. unless the foam is rated for exposure in attics, or a separate ignition barrier is applied.

4.2.4 Buried and Encapsulated Ducts Installed Before Ceiling (Any Climate)

This step-by-step installation detail explains how to install BEDs if the ceiling is installed after the ductwork is installed. This procedure is similar to the method described in Section 4.2.2 for buried ducts. This method includes encapsulation and requires supporting the ductwork before the ceiling is installed. Temporary strapping must be removed before burial.

1.

Install ductwork with a minimum of R-8 duct insulation in accordance with low-profile duct design**.** Where ducts are running parallel to ceiling framing, provide temporary strap supports to hang ducts approximately 2 in. above ceiling plane to allow for thickness of spray foam.

2.

Mastic seal all connections, and pull insulation jackets fully over joints and connections following best practice duct sealing strategies. Tool-tightened tension ties must be applied to the inner and outer liners**.**

3. 

Test total duct leakage to ensure performance levels are met (total duct leakage $\leq 3\ \text{cfm}_{25}/100\ \text{ft}^2$ of conditioned space). Testing should be performed before encapsulation because it may be difficult to correct sealing issues after the application of spray foam.

4. 

Apply at least 1.5 in. of ccSPF to all duct surfaces, including trunks, branches, and register boots. Ducts that are lying directly on the ceiling should be sealed to the top of the gypsum board.

5. 

Install ceiling gypsum board.

6. 

Air seal ceiling plane penetrations, including sealing duct register boots to gypsum board ceiling. Spray foam provides the best sealing benefits for this application**.**

7. 

Install loose-fill insulation to specified depth, and verify that the ducts are covered to the level of design intent. Fiberglass or other mineral fiber insulation must cover the ccSPF by at least 1.5 in. unless the foam is rated for exposure in attics, or a separate ignition barrier is applied.

4.2.5 Encapsulated Ducts in New Construction (Any Climate)

Where necessitated by architectural or structural obstructions, portions of the attic HVAC ducts may be encapsulated in ccSPF but not buried in loose-fill insulation. If the duct is covered by 1.5 in. of ccSPF, leakage will be reduced and a higher effective R-value will be attained. Even when an entire duct system cannot be buried, it is likely that some portions of a duct system may be buried beneath insulation. See Appendix B for a table listing the effective R-values of BEDs for various duct sizes. The exposed foam must either meet the code requirements for attic exposure, or a separate ignition barrier must be applied.

4.3 Installation Procedures for Buried and Encapsulated Ducts in Existing Homes

When retrofitting BEDs into existing homes, the same basic principles, risks, and potential benefits as new construction apply, but in a substantially different context. Most significantly, cost-effectiveness considerations must: (1) take into account the cost of reworking existing ducts and ceiling insulation; (2) determine what is worth replacing; and (3) determine what is worth keeping. The interactions are numerous and highly variable, but the process should begin with a visual survey of the major factors and physical components of the attic and the HVAC ducts.

First, assess the physical access and working clearance of the attic. Can the attic space be reasonably accessed by a crew with materials and equipment needed to complete the job? Assuming the proposed retrofit is not a gut rehab, access must be available without damaging the interior of the home. If existing attic access is inadequate, the cost of providing improved access must be included in the economic evaluation of the project. If working clearance is too limited, the home may not be a good candidate for a BED retrofit.

Second, consider the existing ductwork conditions and placement. What is the physical condition of the ducts? Can they be reused, or is replacement needed? Are the ducts composed of sheet metal, flex-duct, duct board, or a combination of these materials? How are the ducts configured, and how are they secured in place? Are there physical obstacles that would prevent the ducts from being relocated on the attic floor and ultimately insulation buried? Generally the ceiling registers will remain in place unless a more significant retrofit is intended, so a more compact distribution system will not be part of the process. The original ducts were not intended to be low profile, so larger diameter, existing ducts may be difficult to bury beneath insulation.

Finally, as with any duct retrofit work, it is important to understand basic health and safety information related to duct installations in general. In existing homes, inspect the home and systems to determine if the duct improvement work can be performed safely prior to beginning the retrofit. It may be appropriate to refer to standards such as the Building Performance Institute's (BPI) *Technical Standards for the Building Analyst Professional* (BPI 2012) or other protocols. Contractors should refer to appropriate local codes, regulations, professional standards, and common sense as the situation warrants. Take note of the following potential issues.[3]

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[3] The following list of issues is derived from Aldrich and Puttagunta (2011).

- **Structural issues:** If the building and/or the duct system is damaged or structurally unsound, duct retrofits should not be pursued until other repairs are completed.
- **Asbestos, mold, and other contaminants:** If there is an existing mold problem in the building or in the ductwork, or if suspected asbestos-containing material is present, the conditions should be documented and assessed to determine if retrofits can be safely completed. If retrofits cannot be safely completed, the homeowner should be instructed to have the problems addressed by a qualified professional before continuing with duct improvements.
- **Health and safety of the occupants:** If there are people with severe medical conditions living in the home, the situation should be evaluated to ensure that the duct testing and retrofits will not cause adverse health conditions. This could include stirring up dust, blowing cold air into the house, and shutting off systems to complete work during extreme weather.
- **Health and safety of the workers:** If ductwork is located in an attic or other overhead space, caution must be taken to prevent damage to the ceilings in the occupied spaces below. Typically, this requires careful navigation along the ceiling structural members, either ceiling joists or truss bottom chords. Insulation often makes it difficult to identify solid footing, which can lead to damage in ceiling sheetrock below. In most homes, roofing nails penetrate the roof sheathing and extend through the underside of the decking. Where head clearance is low, protective head gear should be worn to prevent cuts or scrapes from the nails. Similarly, workers should wear gloves, goggles, masks, and protective clothing to protect themselves from airborne insulation fibers and dust that are released when ductwork is disturbed. Work should only be undertaken by people comfortable working in constrained spaces and familiar with safe practices for access in attics or other overhead spaces.
- **Make note and be aware of other hazards:** Look for toxic materials, solvents, exposed or knob-and-tube wiring (have an electrician evaluate), non-IC rated can light fixtures, among other issues. Proceed with work only if it can be done safely.

4.3.1 Installation and Planning Steps for All Installations

As with new construction, several steps should be taken to ensure proper installation of BEDs in existing homes. This decision-making process should take into account the advantages, disadvantages, and risks discussed in Section 3.1 as well as the duct design criteria listed above. Many of the steps below reference steps covered in the new construction

1. **Inspect the existing conditions and determine if there are health and safety issues in the home.** This initial inspection will determine the feasibility of applying a BED retrofit to a specific existing home.
2. **Survey and document the layout and condition of existing ducts, and of the existing attic insulation.** In addition to the climate the home is located in, this will determine which BED approach may be appropriate, and the level of duct repair, replacement, and reconfiguration needed in order to accomplish the retrofit.

3. **Create a retrofit plan for the BED application**, based on Steps 1 and 2, including the proposed design of the upgraded system, and the logistical steps needed to conduct the work. Determine whether existing insulation is to be removed or temporarily relocated, how removal will be accomplished, and how the attic ceiling plane air sealing will be incorporated.
4. **Install any needed temporary protection and access, and complete the duct and insulation removal** determined necessary in Step 3. Inspect all work following removal to verify condition of materials to remain.
5. **Relocate or reconfigure ducts** to accommodate BED design. Mastic seal all connections and pull insulation jackets fully over joints and connections following best practice duct sealing strategies.
6. **Test total duct leakage**s to ensure performance levels are met.
7. **Encapsulated and buried and encapsulated ducts: Apply ccSPF to all duct surfaces**, including trunks, branches, and register boots. Ducts that are lying directly on the ceiling should be sealed to the top of the gypsum board. A minimum of 1.5 in. of ccSPF should be applied. Where obstructions cause the bottoms of ducts to be inaccessible for spraying ccSPF (such as when a wide trunk is placed on top of and perpendicular to the ceiling framing), the duct may be placed on top of 1.5-in. thick XPS or polyisocyanurate insulation board, and the spray foam used to encapsulate the duct to the insulation board.
8. **Air seal ceiling plane penetrations.**
9. **Buried (and encapsulated ducts): Install loose-fill** insulation to specified depth covering ducts to the design intent. Fiberglass or other mineral fiber insulation must cover the ccSPF by at least 1.5 in. unless the foam is rated for exposure in attics, or a separate ignition barrier is applied.

5 Verification Procedures and Tests

The degree to which verification procedures and tests are needed with BEDs depends on the amount of duct reconfigurations and equipment modifications performed. For new construction, all of the typical duct and system tests and procedures should be performed. Ducts and systems should be installed in compliance with ACCA Standard 5 (ACCA 2007). This standard has methods for selecting equipment, installing equipment, and installing duct distribution systems. The equipment selection section governs building heat gain/loss load calculations, proper equipment capacity selection, and matching air systems. The equipment installation section governs airflow across the indoor coil, refrigerant charge, electrical requirements, combusting venting systems, and system controls. The duct distribution section covers duct leakage and airflow balance.

For existing systems, only the duct leakage and airflow balancing requirements may be needed. Duct leakage testing involves using a duct blower to measure duct leakage (ASTM 2007). Duct leakage to outdoors must be no more than 8 cfm/100 ft^2 of conditioned floor area, or total duct leakage must be no more than 12 cfm/100 ft^2 of conditioned floor area. Duct leakage is tested at 25 Pa (ICC 2009).

Airflow must be balanced such that individual airflows are within ± 20% of the design flow rate. For existing homes, testing may be done to ensure that airflow rates do not change considerably after the retrofit, and pressures should be tested after installation to verify that the static pressures are within the manufacture recommendations. Total airflow volume at the evaporator must be ± 15% of the design or pre-retrofit flow rate.

For houses with combusting appliances, combustion safety and carbon monoxide testing should be performed. See Aldrich and Puttagunta (2011) for more information.

Ensuring Success

If major HVAC retrofits are planned as part of a project, the following resources may be helpful:

- Air Conditioning Contractors of America (ACCA) Manual D, Manual J, Manual S, Manual T, Manual RS, and Standard 5: HVAC Quality Installation Specification
- EPA document "ENERGY STAR Qualified Homes, Version 3 (Rev. 02) HVAC System Quality Installation Contractor Checklist" (EPA 2012)
- ASHRAE Handbook of Fundamentals 2009
- Sheet Metal and Air Conditioning Contractors National Association *Residential Comfort System Installation Standards Manual*
- ASHRAE Standard 152 - Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems
- ASTM E1554-07: Standard Test Methods for Determining Air Leakage of Air Distribution Systems by Fan Pressurization

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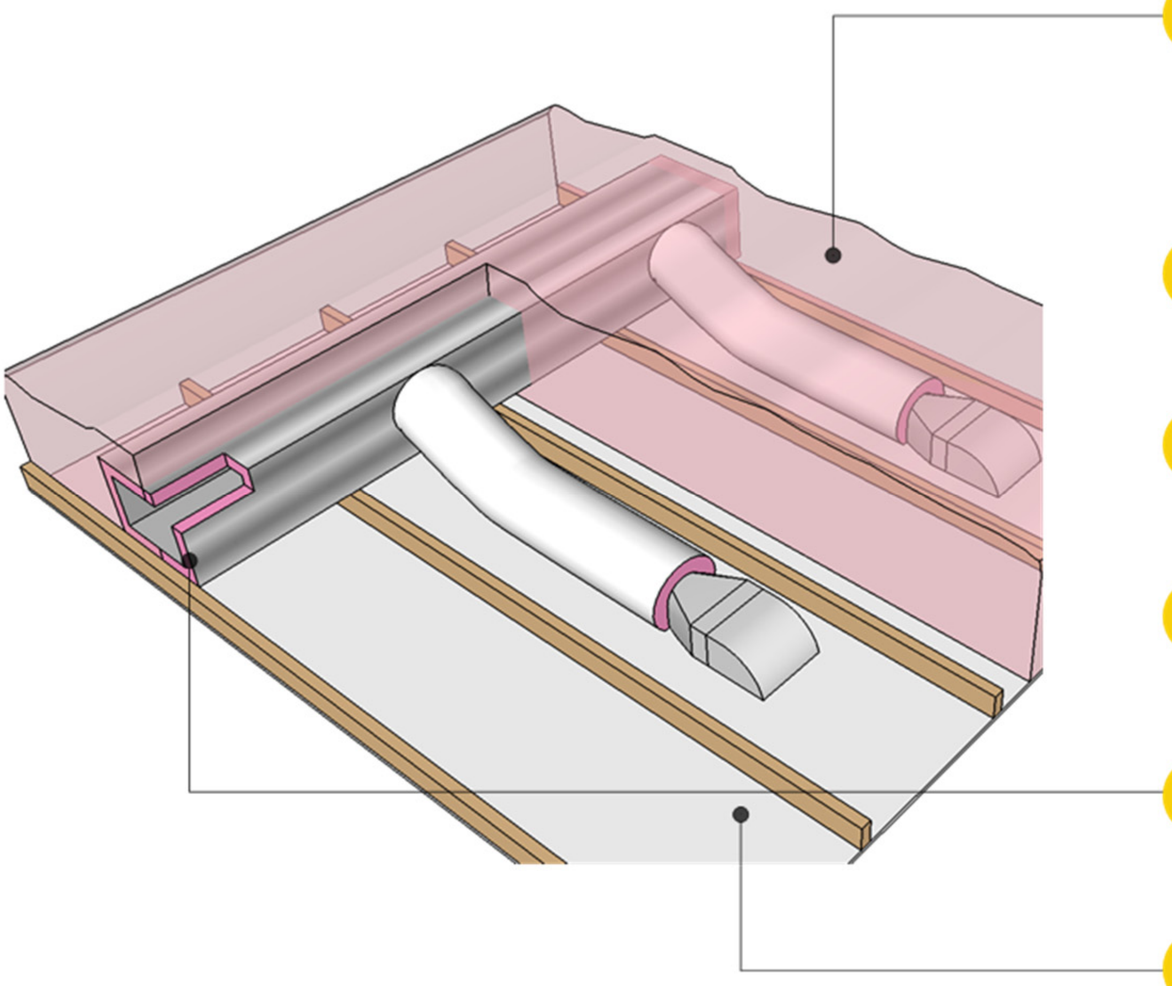
Appendix A: Installation Procedure Diagrams

The figures below show comprehensive diagrams of the step-by-step installation procedures discussed in Section 4.2. These diagrams may be useful as handouts for installers and contractors as well as other stakeholders. The diagrams give a concise description of the installation procedure and may be helpful as a supplement for the more detailed installation procedures given in Section 4.2.



6 Bury ductwork beneath loose-fill insulation to the desired burial level

5 Air seal ceiling plane penetrations

4 Test duct leakage

3 Mastic seal all connections

2 Install ductwork

1 Install ceiling gypsum board

Figure 17. Step-by-step procedure diagram for buried ducts installed after ceiling in new construction

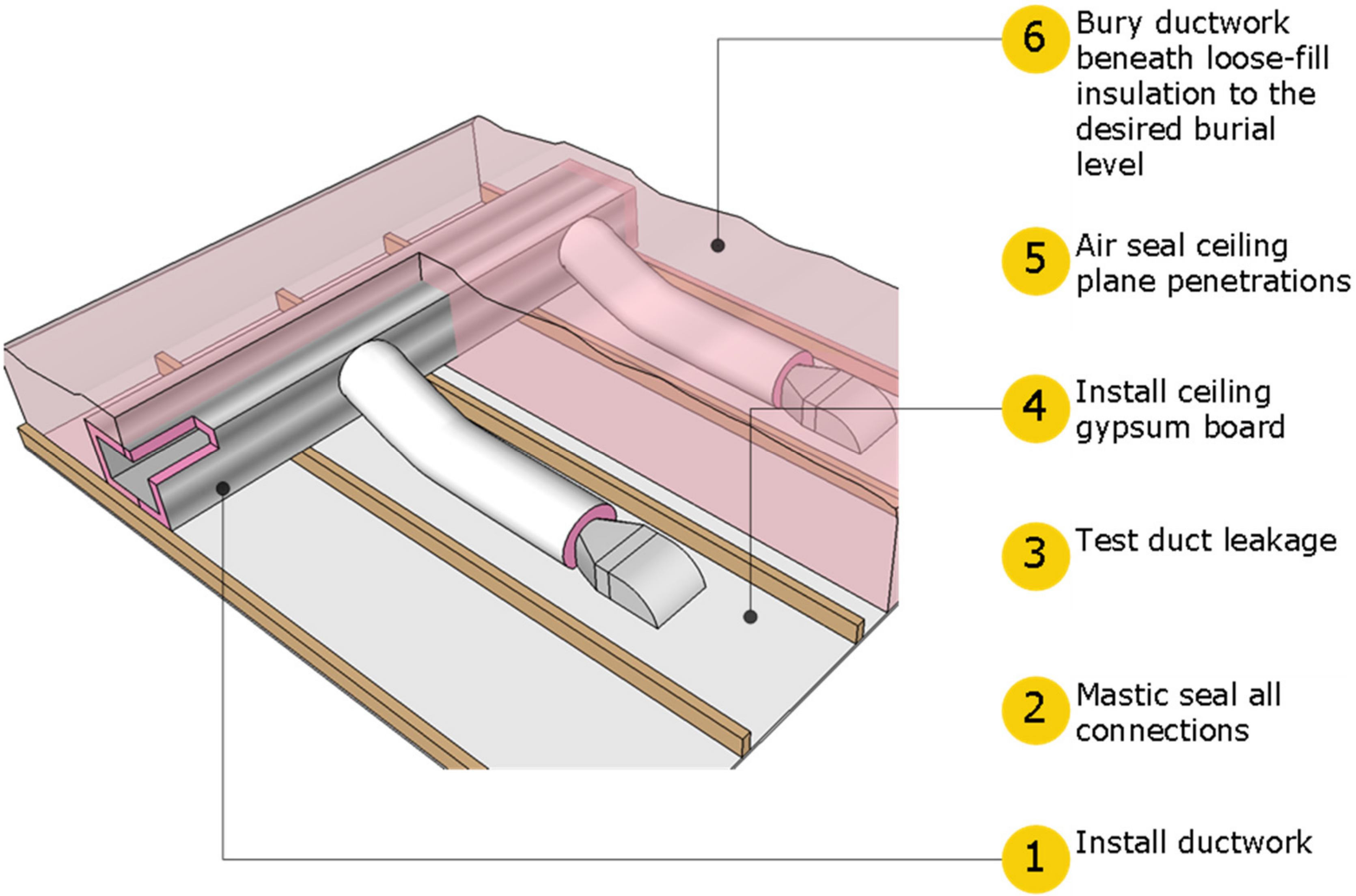
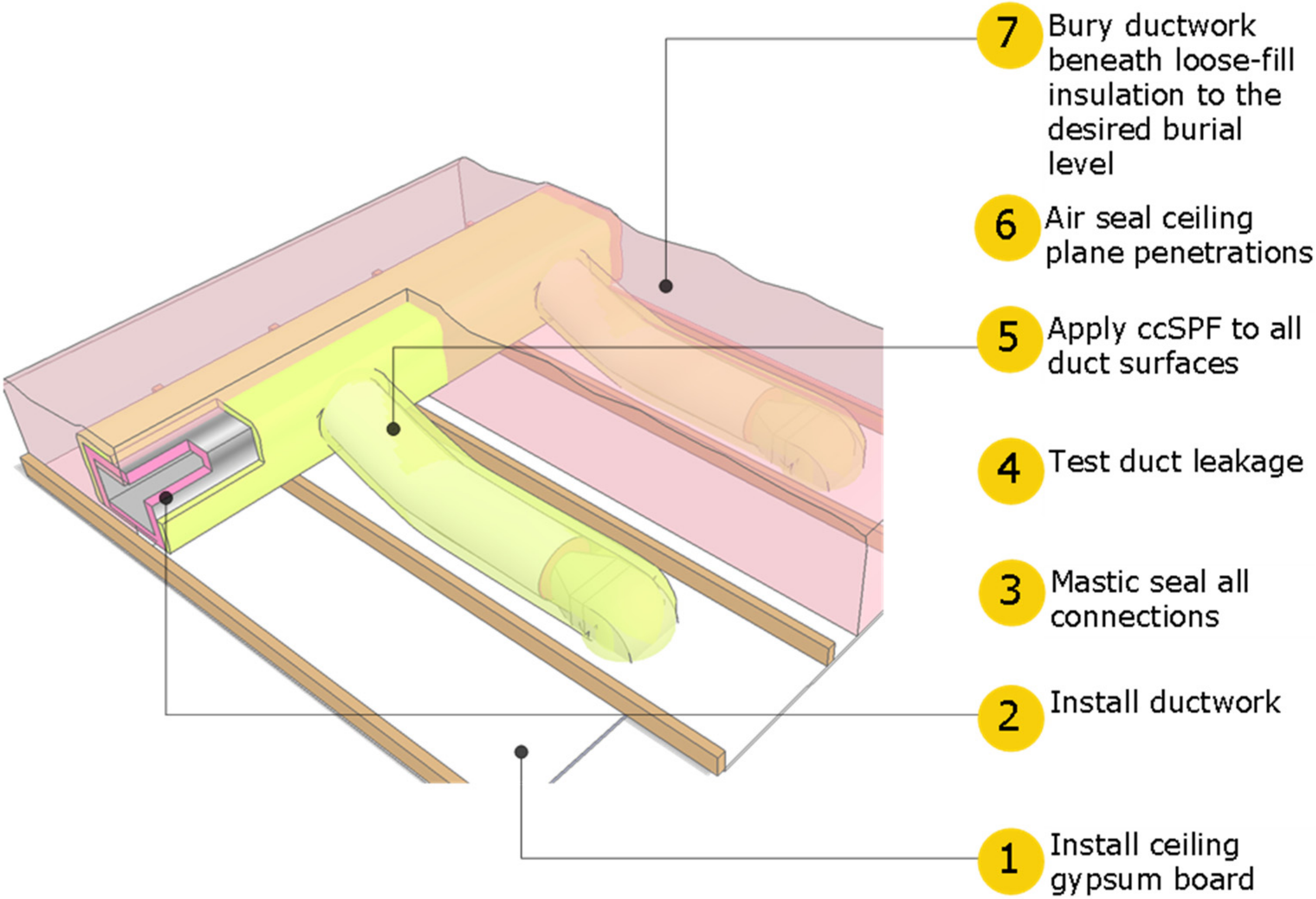


Figure 18. Step-by-step procedure diagram for buried ducts installed before ceiling in new construction



7 Bury ductwork beneath loose-fill insulation to the desired burial level

6 Air seal ceiling plane penetrations

5 Apply ccSPF to all duct surfaces

4 Test duct leakage

3 Mastic seal all connections

2 Install ductwork

1 Install ceiling gypsum board

Figure 19. Step-by-step procedure diagram for buried and encapsulated ducts installed after ceiling in new construction

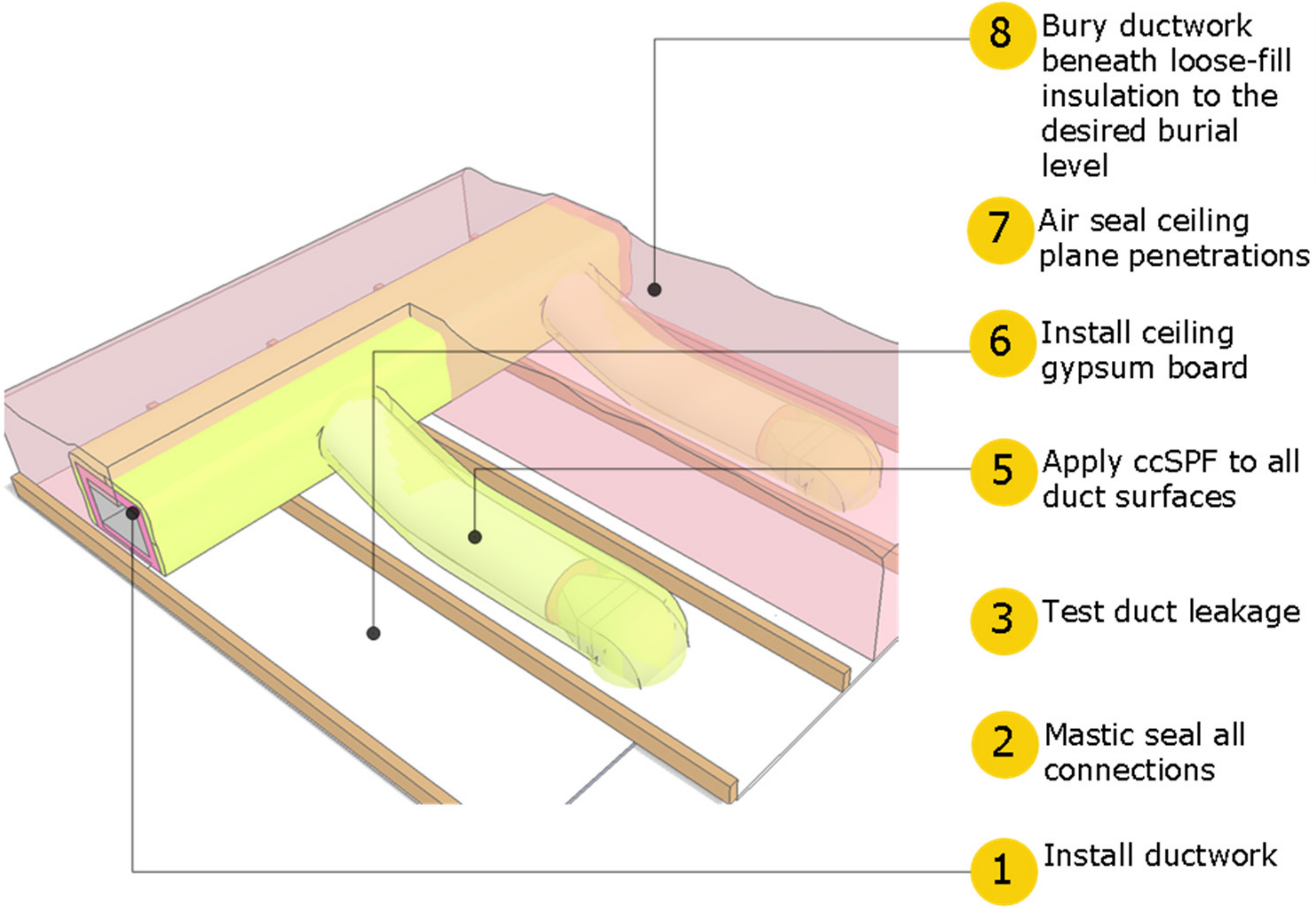
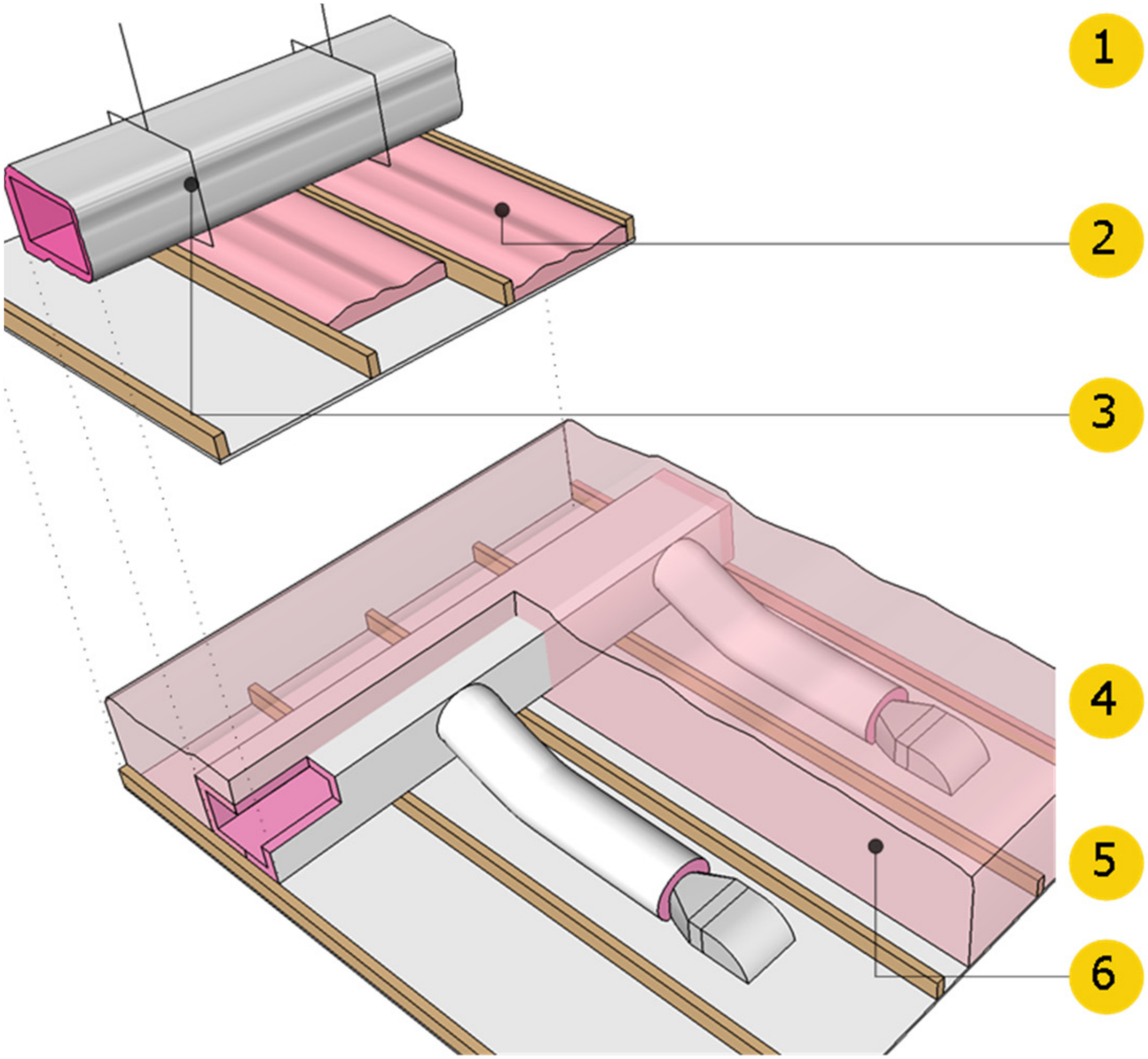


Figure 20. Step-by-step procedure diagram for buried and encapsulated ducts installed before ceiling in new construction



1 Install any needed temporary protection and access

2 Complete insulation removal, as necessary

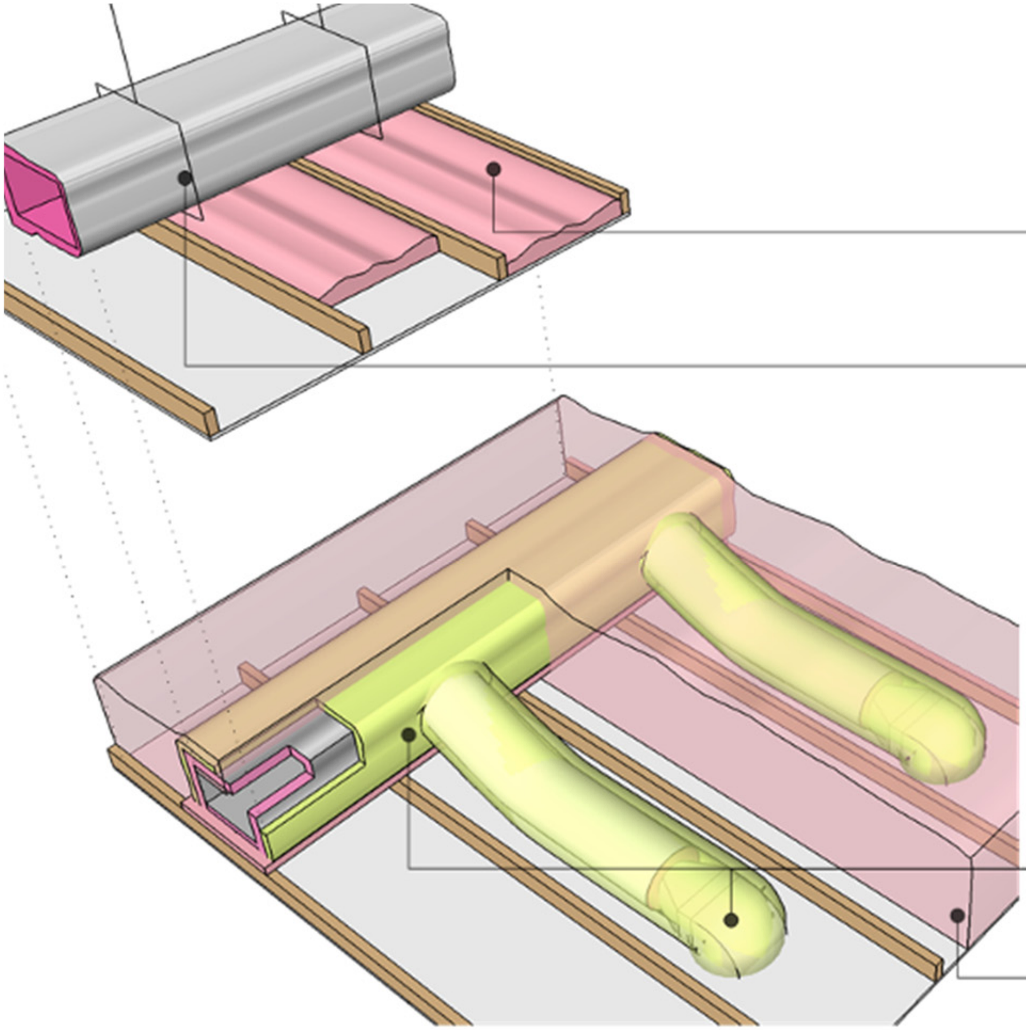
3 Relocate or reconfigure ducts. Cut down or remove supports holding ductwork and plenum boxes

4 Mastic seal all connections and insulate ductwork

5 Test duct leakage

6 Bury ductwork beneath loose-fill insulation to the desired burial level

Figure 21. Step-by-step procedure diagram for buried ducts installed in existing homes



1. Install any needed temporary protection and access
2. Complete insulation removal, as necessary
3. Relocate or reconfigure ducts. Cut down or remove supports holding ductwork and plenum boxes
4. Mastic seal all connections and insulate ductwork
5. Test duct leakage
6. Apply ccSPF to all duct surfaces
7. Bury ductwork beneath loose-fill insulation to the desired burial level

Figure 22. Step-by-step procedure diagram for buried and encapsulated ducts installed in existing homes

Appendix B: Effective R-Value Tables

Thermal resistances for most duct insulation products are typically listed as a rated, nominal R-value, which is calculated for the insulation material lying flat. When the materials are wrapped around ductwork, however, the "true" R-value of the insulation can be significantly different than the nominal values. Furthermore, the nominal R-value excludes the inner and outer surface films of air (Palmiter and Kruse 2006).

For the purposes of evaluating various duct systems, thermal resistances of duct insulation may be reported using three metrics:

- **Nominal R-values**, which are the listed values for the material, do not include the impact of duct geometry, surface film resistances, and heat transfer between the air inside the duct and conditioned space
- **Apparent R-values** account for duct geometry and surface film resistances. Apparent R-values do not include heat transfer between the air inside the ducts and the conditioned space. As a result, apparent R-values are used for comparing experimental results to predicted values and are not useful for efficiency comparisons.
- **Effective R-values** can be considered the "true" R-value of the duct insulation. Effective R-values include duct geometry effects, surface film resistances, and heat transfer between air inside the duct and conditioned space. For traditional hung ductwork and encapsulated ducts, effective R-values are identical to apparent R-values. For buried ducts, effective R-values can be considerably different than apparent R-values due to the significant heat transfer between the ductwork and conditioned space. Effective R-values are necessary to calculate energy savings associated with buried (and encapsulated) ducts.

The tables below list effective R-values for flex-duct of various sizes and insulation levels. These tables include traditional ducts, encapsulated ducts, buried ducts, and buried and encapsulated ducts. Effective R-values are also compared to nominal R-values in the tables.

Table 12. Effective R-Values of Round Insulated Flexible Ducts

Duct Inner Diameter (in.)	R-4.2 Flex Duct	R-6 Flex Duct	R-8 Flex Duct
4	4.1	5.0	6.0
6	4.4	5.6	6.7
8	4.6	5.9	7.2
10	4.7	6.1	7.5
12	4.9	6.3	7.7
14	4.9	6.4	7.9
16	5.0	6.5	8.0

Source: Shapiro et al. (2012)

Table 13. Effective R-Values of Encapsulated Round Flexible Ducts by Insulation Thickness

	R-4.2 Flex Duct			R-6 Flex Duct			R-8 Flex Duct		
ccSPF Thickness	**1.5-in.**	**2-in.**	**2.5-in.**	**1.5-in.**	**2-in.**	**2.5-in.**	**1.5-in.**	**2-in.**	**2.5-in.**
Nominal R-Value	**14.3**	**17.6**	**21.0**	**16.1**	**19.4**	**22.8**	**18.1**	**21.4**	**24.8**
4-in. diameter	9.0	10.4	11.6	9.4	10.6	11.7	9.9	10.9	11.9
6-in. diameter	10.4	12.0	13.6	11.0	12.5	13.9	11.6	13.0	14.3
8-in. diameter	11.3	13.1	14.9	12.0	13.7	15.4	12.7	14.4	15.9
10-in. diameter	11.9	13.9	15.9	12.7	14.7	16.5	13.6	15.4	17.1
12-in. diameter	12.3	14.5	16.6	13.3	15.4	17.3	14.3	16.2	18.1
14-in. diameter	12.7	15.0	17.2	13.7	15.9	18.0	14.8	16.9	18.9
16-in. diameter	13.0	15.4	17.7	14.1	16.4	18.6	15.2	17.4	19.5

Source: Shapiro et al. (2012)

Table 14. Effective R-Values of Buried Round Ducts

	R-4.2 Flex Duct			R-6 Flex Duct			R-8 Flex Duct		
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

Source: Shapiro et al. (2012)

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

	R-4.2 Flex Duct			R-6 Flex Duct			R-8 Flex Duct		
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

Source: Shapiro et al. (2012)

Appendix C: Energy Savings by Climate and Roof Slope

Source energy savings as a percentage of total house energy use were calculated using BEoptE+ 1.3 for a 2,400-ft^2 single-story home built with slab-on-grade construction. Energy savings are compared to the Building America Benchmark (Hendron and Engebrecht 2010) and an improved benchmark that includes the IECC 2012 requirements for infiltration (5 ACH50) and duct sealing (4 cfm/100 ft^2 of conditioned living space). All modeled options are improvements to the improved benchmark. All ductwork and AHUs are assumed to be within the attic, which is consistent with the benchmark assumptions. Heating appliances are assumed to use natural gas. Modeling results by climate and roof slope are shown in Table 17 through Table 28.

While using ccSPF to create a sealed attic will undoubtedly reduce the infiltration rate of the building, there are few quantifiable data about the infiltration reduction resulting from simply spray-foaming the roof deck. The lack of quantifiable data makes modeling the impact of roof deck spray foam difficult without simply assuming an infiltration reduction. As a result, all modeled configurations have the same infiltration rate as the improved benchmark in an effort to avoid trying to make assumptions about infiltration without data.

Modeling ductwork air leakage is somewhat tricky because the IECC and BA Benchmark define total duct leakage using different metrics. The IECC sets a maximum leakage in terms of cfm/100 ft^2 of conditioned floor area. The BA Benchmark uses leakage as a fraction of AHU flow. Comparisons can be drawn between the two standards, however, because the BA Benchmark is meant to be consistent with the 2009 IECC. The leakage rates for the improved benchmark can be determined by looking at the percent reduction in leakage between the 2009 and 2012 IECC. The IECC goes from a maximum leakage rate of 12 cfm/100 ft^2 in 2009 to 4 cfm/100 ft^2 in 2012. This 67% reduction is applied to the BA Benchmark, which reduces the leakage rate from 15% to 5%.

Table 16. Duct Leakage Rates (% of AHU Flow) for BEopt Modeling

	Supply	Return	AHU Supply	AHU Return	Total
Benchmark	9	1	1	4	15
Improved Benchmark	1.5	1.5	1	1	5
Partially Buried	1.5	1.5	1	1	5
Fully Buried	1.5	1.5	1	1	5
Deeply Buried	1.5	1.5	1	1	5
Unvented	1.5	1.5	1	1	5
Encapsulated	0	0	1	1	2
Partially Buried and Encapsulated	0	0	1	1	2
Fully Buried and Encapsulated	0	0	1	1	2
Deeply Buried and Encapsulated	0	0	1	1	2
Interior Ducts	1.5	1.5	1	1	5

Splitting up the specific leakage rates for the supply, return, AHU supply, and AHU return was not as straightforward as taking the BA Benchmark and reducing each component by two thirds.

Since the ccSPF will eliminate duct leakage, the supply and return duct leakage rates for the encapsulated cases will be zero. BEopt does not allow unbalanced duct leakage, however, so the portion of the duct leakage attributed to each component of the system had to be reapportioned. The AHU leakage was assumed to be 2%, which is the maximum stated rate in the 2012 IECC. The remaining leakage was equally apportioned to the supply and return sides. The resulting leakage rates for modeling are shown in Table 16.

Table 17. Jacksonville, Florida (2A)

	Roof slope			
Assembly (Attic R-value)	**4:12**	**6:12**	**8:12**	**10:12**
Benchmark (R-30)[a]	0.0%	0.0%	0.0%	0.0%
Improved benchmark (R-30)[a,b]	5.9%	5.9%	5.9%	5.9%
Partially-buried (R-33)	N/A	N/A	N/A	N/A
Fully-buried (R-42)	N/A	N/A	N/A	N/A
Deeply-buried (R-51)	N/A	N/A	N/A	N/A
Unvented (R-30)[a]	7.5%	7.3%	7.1%	6.8%
Encapsulated (R-30)[a]	7.1%	7.0%	7.1%	7.0%
Partially-buried & encapsulated (R-37)	8.3%	8.3%	8.4%	8.3%
Fully-buried & encapsulated (R-46)	9.1%	9.1%	9.1%	9.1%
Deeply-buried & encapsulated (R-54)	9.6%	9.7%	9.7%	9.6%
Interior ducts (R-30)[a]	8.9%	8.8%	8.9%	8.8%

[a] Benchmark ceiling or roof deck insulation is R-30 in Zone 2A. Ceiling insulation R-values for buried ducts may be higher than the benchmark.

[b] Improved Benchmark includes IECC 2012 requirements for infiltration (5 ACH_{50}) and duct sealing (4 cfm per 100 ft^2 conditioned living space).

Table 18. Tucson, Arizona (2B)

	Roof slope			
Assembly (Attic R-value)	**4:12**	**6:12**	**8:12**	**10:12**
Benchmark (R-30)[a]	0.0%	0.0%	0.0%	0.0%
Improved benchmark (R-30)[a,b]	5.1%	5.1%	5.1%	5.1%
Partially-buried (R-33)	6.5%	6.5%	6.5%	6.5%
Fully-buried (R-42)	8.1%	8.1%	8.1%	8.1%
Deeply-buried (R-51)	9.3%	9.4%	9.3%	9.3%
Unvented (R-30)[a]	7.9%	7.5%	7.1%	6.7%
Encapsulated (R-30)[a]	6.9%	6.8%	6.8%	6.8%
Partially-buried & encapsulated (R-37)	8.7%	8.6%	8.6%	8.6%
Fully-buried & encapsulated (R-46)	9.8%	9.8%	9.7%	9.7%
Deeply-buried & encapsulated (R-54)	10.5%	10.6%	10.6%	10.5%
Interior ducts (R-30)[a]	9.6%	9.5%	9.5%	9.4%

[a] Benchmark ceiling or roof deck insulation is R-30 in Zone 2B. Ceiling insulation R-values for buried ducts may be higher than the benchmark.

[b] Improved Benchmark includes IECC 2012 requirements for infiltration (5 ACH_{50}) and duct sealing (4 cfm per 100 ft^2 conditioned living space).

Table 19. Atlanta, Georgia (3A)

	Roof slope			
Assembly (Attic R-value)	4:12	6:12	8:12	10:12
Benchmark (R-30)[a]	0.0%	0.0%	0.0%	0.0%
Improved benchmark (R-30)[a,b]	7.6%	7.6%	7.6%	7.7%
Partially-buried (R-33)	N/A	N/A	N/A	N/A
Fully-buried (R-42)	N/A	N/A	N/A	N/A
Deeply-buried (R-51)	N/A	N/A	N/A	N/A
Unvented (R-30)[a]	10.6%	10.3%	9.9%	9.5%
Encapsulated (R-30)[a]	9.1%	9.2%	9.2%	9.2%
Partially-buried & encapsulated (R-37)	11.1%	11.1%	11.1%	11.1%
Fully-buried & encapsulated (R-46)	12.1%	12.3%	12.2%	12.2%
Deeply-buried & encapsulated (R-54)	12.9%	13.1%	13.0%	13.0%
Interior ducts (R-30)[a]	11.9%	11.9%	11.9%	11.9%

[a] Benchmark ceiling or roof deck insulation is R-30 in Zone 3A. Ceiling insulation R-values for buried ducts may be higher than the benchmark.

[b] Improved Benchmark includes IECC 2012 requirements for infiltration (3 ACH_{50}) and duct sealing (4 cfm per 100 ft^2 conditioned living space).

Table 20. Las Vegas, NV (3B)

	Roof slope			
Assembly (Attic R-value)	4:12	6:12	8:12	10:12
Benchmark (R-30)[a]	0.0%	0.0%	0.0%	0.0%
Improved benchmark (R-30)[a,b]	7.7%	7.6%	7.6%	7.7%
Partially-buried (R-33)	9.2%	9.2%	9.2%	9.2%
Fully-buried (R-42)	10.9%	10.9%	10.9%	10.9%
Deeply-buried (R-51)	12.2%	12.2%	12.2%	12.2%
Unvented (R-30)[a]	9.3%	10.2%	9.7%	9.3%
Encapsulated (R-30)[a]	9.5%	9.5%	9.5%	9.5%
Partially-buried & encapsulated (R-37)	11.4%	11.5%	11.4%	11.4%
Fully-buried & encapsulated (R-46)	12.6%	12.7%	12.7%	12.6%
Deeply-buried & encapsulated (R-54)	13.5%	13.6%	13.6%	13.5%
Interior ducts (R-30)[a]	12.4%	12.5%	12.4%	12.4%

[a] Benchmark ceiling or roof deck insulation is R-30 in Zone 3B. Ceiling insulation R-values for buried ducts may be higher than the benchmark.

[b] Improved Benchmark includes IECC 2012 requirements for infiltration (3 ACH_{50}) and duct sealing (4 cfm per 100 ft^2 conditioned living space).

Table 21. San Francisco, California (3C)

	Roof slope			
Assembly (Attic R-value)	4:12	6:12	8:12	10:12
Benchmark (R-30)[a]	0.0%	0.0%	0.0%	0.0%
Improved benchmark (R-30)[a,b]	7.4%	7.4%	7.4%	7.4%
Partially-buried (R-33)	N/A	N/A	N/A	N/A
Fully-buried (R-42)	N/A	N/A	N/A	N/A
Deeply-buried (R-51)	N/A	N/A	N/A	N/A
Unvented (R-30)[a]	11.9%	11.7%	11.4%	11.0%
Encapsulated (R-30)[a]	8.5%	8.5%	8.5%	8.5%
Partially-buried & encapsulated (R-37)	10.0%	10.1%	10.1%	10.1%
Fully-buried & encapsulated (R-46)	10.9%	11.1%	11.1%	11.1%
Deeply-buried & encapsulated (R-54)	11.6%	11.8%	11.8%	11.8%
Interior ducts (R-30)[a]	10.5%	10.5%	10.5%	10.5%

[a] Benchmark ceiling or roof deck insulation is R-30 in Zone 3C. Ceiling insulation R-values for buried ducts may be higher than the benchmark.

[b] Improved Benchmark includes IECC 2012 requirements for infiltration (3 ACH_{50}) and duct sealing (4 cfm per 100 ft^2 conditioned living space).

Table 22. Lexington, Kentucky (4A)

	Roof slope			
Assembly (Attic R-value)	4:12	6:12	8:12	10:12
Benchmark (R-38)[a]	0.0%	0.0%	0.0%	0.0%
Improved benchmark (R-38)[a,b]	10.0%	10.0%	10.0%	10.1%
Partially-buried (R-38)	N/A	N/A	N/A	N/A
Fully-buried (R-42)	N/A	N/A	N/A	N/A
Deeply-buried (R-51)	N/A	N/A	N/A	N/A
Unvented (R-38)[a]	13.4%	13.0%	12.6%	12.1%
Encapsulated (R-38)[a]	11.8%	11.7%	11.8%	11.8%
Partially-buried & encapsulated (R-38)	12.7%	12.6%	12.6%	12.7%
Fully-buried & encapsulated (R-46)	13.7%	13.8%	13.8%	13.8%
Deeply-buried & encapsulated (R-54)	14.6%	14.7%	14.8%	14.8%
Interior ducts (R-38)[a]	14.8%	14.8%	14.8%	14.8%

[a] Benchmark ceiling or roof deck insulation is R-38 in Zone 4A. Ceiling insulation R-values for buried ducts may be higher than the benchmark.

[b] Improved Benchmark includes IECC 2012 requirements for infiltration (3 ACH_{50}) and duct sealing (4 cfm per 100 ft^2 conditioned living space).

Table 23. Albuquerque, New Mexico (4B)

Assembly (Attic R-value)	Roof slope 4:12	6:12	8:12	10:12
Benchmark (R-38)[a]	0.0%	0.0%	0.0%	0.0%
Improved benchmark (R-38)[a,b]	8.0%	8.0%	8.1%	8.1%
Partially-buried (R-38)	8.9%	9.0%	9.0%	9.0%
Fully-buried (R-42)	10.0%	10.0%	10.1%	10.0%
Deeply-buried (R-51)	11.3%	11.5%	11.5%	11.5%
Unvented (R-38)[a]	11.3%	10.9%	10.4%	10.0%
Encapsulated (R-38)[a]	9.7%	9.7%	9.7%	9.7%
Partially-buried & encapsulated (R-38)	10.5%	10.5%	10.6%	10.6%
Fully-buried & encapsulated (R-46)	11.6%	11.7%	11.8%	11.7%
Deeply-buried & encapsulated (R-54)	12.6%	12.8%	12.8%	12.8%
Interior ducts (R-38)[a]	12.6%	12.6%	12.6%	12.6%

[a] Benchmark ceiling or roof deck insulation is R-38 in Zone 4B. Ceiling insulation R-values for buried ducts may be higher than the benchmark.

[b] Improved Benchmark includes IECC 2012 requirements for infiltration (3 ACH_{50}) and duct sealing (4 cfm per 100 ft^2 conditioned living space).

Table 24. Seattle, Washington (4C)

Assembly (Attic R-value)	Roof slope 4:12	6:12	8:12	10:12
Benchmark (R-38)[a]	0.0%	0.0%	0.0%	0.0%
Improved benchmark (R-38)[a,b]	8.7%	8.8%	8.8%	8.8%
Partially-buried (R-38)	N/A	N/A	N/A	N/A
Fully-buried (R-42)	N/A	N/A	N/A	N/A
Deeply-buried (R-51)	N/A	N/A	N/A	N/A
Unvented (R-38)[a]	13.2%	12.8%	12.4%	11.9%
Encapsulated (R-38)[a]	10.8%	10.9%	10.9%	10.9%
Partially-buried & encapsulated (R-38)	11.8%	11.8%	11.9%	11.9%
Fully-buried & encapsulated (R-46)	12.9%	13.0%	13.0%	13.0%
Deeply-buried & encapsulated (R-54)	13.8%	14.0%	14.0%	14.0%
Interior ducts (R-38)[a]	14.0%	14.0%	14.0%	14.0%

[a] Benchmark ceiling or roof deck insulation is R-38 in Zone 4C. Ceiling insulation R-values for buried ducts may be higher than the benchmark.

[b] Improved Benchmark includes IECC 2012 requirements for infiltration (3 ACH_{50}) and duct sealing (4 cfm per 100 ft^2 conditioned living space).

Table 25. Boston, Massachusetts (5A)

Assembly (Attic R-value)	Roof slope 4:12	6:12	8:12	10:12
Benchmark (R-38)[a]	0.0%	0.0%	0.0%	0.0%
Improved benchmark (R-38)[a,b]	13.0%	13.0%	13.0%	13.0%
Partially-buried (R-38)	N/A	N/A	N/A	N/A
Fully-buried (R-42)	N/A	N/A	N/A	N/A
Deeply-buried (R-51)	N/A	N/A	N/A	N/A
Unvented (R-38)[a]	16.5%	16.1%	15.7%	15.1%
Encapsulated (R-38)[a]	14.9%	14.9%	14.9%	14.9%
Partially-buried & encapsulated (R-38)	15.9%	15.9%	15.9%	16.0%
Fully-buried & encapsulated (R-46)	17.0%	17.1%	17.1%	17.1%
Deeply-buried & encapsulated (R-54)	17.9%	18.1%	18.1%	18.1%
Interior ducts (R-38)[a]	18.1%	18.1%	18.1%	18.1%

[a] Benchmark ceiling or roof deck insulation is R-38 in Zone 5A. Ceiling insulation R-values for buried ducts may be higher than the benchmark.

[b] Improved Benchmark includes IECC 2012 requirements for infiltration (3 ACH_{50}) and duct sealing (4 cfm per 100 ft^2 conditioned living space).

Table 26. Denver, Colorado (5B)

Assembly (Attic R-value)	Roof slope 4:12	6:12	8:12	10:12
Benchmark (R-38)[a]	0.0%	0.0%	0.0%	0.0%
Improved benchmark (R-38)[a,b]	9.9%	10.0%	10.0%	10.0%
Partially-buried (R-38)	11.1%	11.1%	11.2%	11.2%
Fully-buried (R-42)	12.3%	12.4%	12.4%	12.4%
Deeply-buried (R-51)	13.8%	14.1%	14.1%	14.1%
Unvented (R-38)[a]	13.8%	13.3%	12.8%	12.2%
Encapsulated (R-38)[a]	11.9%	11.9%	12.0%	12.0%
Partially-buried & encapsulated (R-38)	12.9%	13.0%	13.0%	13.0%
Fully-buried & encapsulated (R-46)	14.2%	14.3%	14.4%	14.4%
Deeply-buried & encapsulated (R-54)	15.3%	15.5%	15.5%	15.6%
Interior ducts (R-38)[a]	15.4%	15.5%	15.5%	15.5%

[a] Benchmark ceiling or roof deck insulation is R-38 in Zone 5B. Ceiling insulation R-values for buried ducts may be higher than the benchmark.

[b] Improved Benchmark includes IECC 2012 requirements for infiltration (3 ACH_{50}) and duct sealing (4 cfm per 100 ft^2 conditioned living space).

Table 27. Madison, Wisconsin (6A)

	Roof slope			
Assembly (Attic R-value)	4:12	6:12	8:12	10:12
Benchmark (R-49)[a]	0.0%	0.0%	0.0%	0.0%
Improved benchmark (R-49)[a,b]	14.3%	14.2%	14.3%	14.3%
Partially-buried (R-49)	N/A	N/A	N/A	N/A
Fully-buried (R-49)	N/A	N/A	N/A	N/A
Deeply-buried (R-51)	N/A	N/A	N/A	N/A
Unvented (R-49)[a]	18.2%	17.6%	17.2%	16.6%
Encapsulated (R-49)[a]	16.3%	16.3%	16.3%	16.3%
Partially-buried & encapsulated (R-49)	17.3%	17.3%	17.4%	17.4%
Fully-buried & encapsulated (R-49)	17.6%	17.6%	17.6%	17.7%
Deeply-buried & encapsulated (R-54)	18.3%	18.4%	18.5%	18.5%
Interior ducts (R-49)[a]	19.9%	20.0%	20.0%	20.0%

[a] Benchmark ceiling or roof deck insulation is R-49 in Zone 6A. Ceiling insulation R-values for buried ducts may be higher than the benchmark.

[b] Improved Benchmark includes IECC 2012 requirements for infiltration (3 ACH_{50}) and duct sealing (4 cfm per 100 ft^2 conditioned living space).

Table 28. Billings, Montana (6B)

	Roof slope			
Assembly (Attic R-value)	4:12	6:12	8:12	10:12
Benchmark (R-49)[a]	0.0%	0.0%	0.0%	0.0%
Improved benchmark (R-49)[a,b]	13.4%	13.5%	13.5%	13.5%
Partially-buried (R-49)	14.9%	15.0%	15.0%	15.0%
Fully-buried (R-49)	15.7%	15.8%	15.8%	15.8%
Deeply-buried (R-51)	16.7%	16.7%	16.8%	16.8%
Unvented (R-49)[a]	18.4%	17.9%	17.5%	16.9%
Encapsulated (R-49)[a]	15.8%	15.8%	15.9%	15.9%
Partially-buried & encapsulated (R-49)	17.1%	17.1%	17.1%	17.2%
Fully-buried & encapsulated (R-49)	17.5%	17.5%	17.5%	17.5%
Deeply-buried & encapsulated (R-54)	18.3%	18.4%	18.4%	18.4%
Interior ducts (R-49)[a]	20.2%	20.2%	20.3%	20.3%

[a] Benchmark ceiling or roof deck insulation is R-49 in Zone 6B. Ceiling insulation R-values for buried ducts may be higher than the benchmark.

[b] Improved Benchmark includes IECC 2012 requirements for infiltration (3 ACH_{50}) and duct sealing (4 cfm per 100 ft^2 conditioned living space).

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