The Benefits of Buried Ducts - Beyond What We Know Today

Rebecca EVANS[1], Simon PALLIN[1]* PhD, Keith SAECHAO[1]

[1]Frontier Energy, Inc.
Davis, CA, USA
revans@frontierenergy.com, spallin@frontierenergy.com, ksaechao@frontierenergy.com

* Corresponding Author

ABSTRACT

Burying your ventilation ducts inside attic insulation can save you money. Yet, this installation approach is not very common. Traditionally, and most commonly, ducts are suspended from the roof trusses and therefore located in the attic space. However, when ducts are partially or fully buried within loose fill insulation, the overall thermal resistance between the air inside the ducts and that of the attic increases significantly, resulting in less energy losses. There is also an expected increase in service-life of buried ducts since, when buried, they are not as exposed to extreme attic temperatures as suspended ducts.
Some of the previous work on buried ducts has underestimated the thermal benefits of buried ducts. This paper presents how the thermal performance of buried ducts can be more accurately assessed depending on various variables such as duct diameter, duct insulation value, attic insulation level and material, as well as temperature boundary conditions.
In addition, this paper investigates reasons for a currently lower adoption rate of buried ducts and also identifies potential market barriers, installations issues, and any other industry concerns. Furthermore, other reasons are considered related to the complexity of the compliance and enforcement process, and any other regulatory context which complicates the adoption of buried ducts.

1. INTRODUCTION

Buried ducts refer to ducts that are entirely or partially surrounded by loose-fill insulation in an attic. Typically, ducts in the attic of a home are suspended, meaning they are strapped to roofing members and are raised above the attic floor insulation. Buried ducts, in comparison to suspended ducts, reduce conductive and radiant heat transfer between the attic and the ducts (Shapiro, 2013) and therefore reduce energy distribution losses in the HVAC system.

Unconditioned spaces such as the attic of a residential home may reach extreme temperatures of 130°F (54.4°C) or higher during summer months (Zoeller, 2009). Extreme temperatures in the attic have a large impact on the attic duct heat transfer and subsequently the overall efficiency of the cooling system. The practice of burying ducts increases the thermal resistance, also known as R-value, between the ducts and the attic space and thus reduces energy transfer between the two. A visualization of ducts buried in an attic can be seen in Figure 1.

The term effective R-value was introduced by Griffiths and Zuluaga in 2004 and was used to describe the thermal benefits of burying ducts inside attic insulation (Griffiths & Zuluaga, 2004). In this study, the effective R-value was introduced to quantify buried ducts as if they were typical suspended ducts in the attic. The effective R-value accounts for the thermal resistance provided by the loose-fill insulation and the duct insulation around the ducts. A finite-element analysis model was used in calculating the effective R-value for different duct diameters and levels of insulation. However, in this analysis, the heat flow between the duct and the interior did not depend on attic temperature, leading to underestimated effective R-values.

Figure 1: Duct fully buried inside attic loose fill insulation and resting on top of the ceiling drywall.

In 2013, Shapiro et al. explored an approach to calculating the effective R-value for buried ducts (Shaprio, Magee, & Zoeller, 2013). However, this analysis on effective R-value fails to explain how the heat flow between the ducts and the attic is calculated. Furthermore, this analysis concludes that R-value is independent of attic temperature which contradicts what is presented in this paper. One statement made in multiple reports by Shapiro et al. (Shapiro, Zoeller, & Mantha, 2013) (Shaprio, Magee, & Zoeller, 2013) is the effective R-value of buried ducts increases with increasing duct diameter. However, this claim can be misinterpreted if not provided with further information. If the duct diameter increases but the level of insulation stays the same, the effective R-value does not increase.

Overall, previous work on buried ducts has largely underestimated the thermal performance of buried ducts. Existing studies typically underestimate effective R-values in comparison to the analysis of this paper. Previous work done by Salonvaara et al. is one instance of similar results, but the impact of the thermal boundary conditions is not discussed (Salonvaara et al., 2019). The thermal performance of buried ducts can be more accurately determined based on duct diameter, temperature boundary conditions, insulation level and material, and duct insulation. This paper presents a polynomial regression equation that incorporates these factors and is dependent on attic temperature to calculate effective R-value. This paper analyzes a 2,100 ft^2 (195 m^2) single-family home model simulated in cities across the United States. Information gathered from each simulation includes attic temperature and if the heating and cooling systems are running, all given hourly. These results are then used to determine the overall effective R-value in each city.

Currently, the implementation of buried ducts is relatively low in the United States despite several field studies proving the energy benefits from buried ducts (Griffiths et al., 2002; Shapiro, Zoeller, & Mantha, 2013; HIRL, 2016; Mallay, 2016). According to data from CalCERTS, in 2019, only 11 new single-family homes in California installed buried ducts (CalCERTS, 2023). There are several potential market barriers, industry concerns, and installation issues that will be discussed in this paper. One of the main barriers is the concern of condensation in the attic with the use of buried ducts. In 2002, Griffiths et al. presented a field study where attic ducts were installed under insulation (Griffiths et al., 2002). This study took place in Florida, a hot and humid climate, and looked at the potential for condensation issues. However, the study found no significant condensation problems. Additionally, one of the largest barriers to overcome for the adoption of buried ducts is the complexity of the compliance and enforcement process which will be looked at further in this paper.

2. EFFECTIVE R-VALUE OF BURIED DUCTS

2.1 Temperature Dependency

The effective R-value of ducts buried in attic insulation can be estimated using the temperatures and thermal resistances between the air in the attic, ducts, and interior of the house. However, finding the effective R-value of buried ducts is not a straight-forward approach. There are three different temperature conditions and, thus, three temperature gradients to account for. According to Fourier's law, there is a linear dependency between heat transfer and temperature gradients between two boundaries. Heat travels from areas of higher temperature to areas of lower temperature, and Fourier's law shows that the rate of this flow is determined by the temperature difference between two points and the thermal conductivity of the material through which the heat flows. If the temperature gradient doubles, then the heat transferred will also increase. However, in the case of buried ducts, there are three temperature boundaries, so the linear dependency doesn't apply.

Figure 2 shows the simulation output of heat flux magnitudes for two different attic temperature conditions. Both sides of the figure assume a 60°F (15.6°C) duct air temperature and a 75°F (23.9°C) indoor temperature. The third temperature boundary condition, the attic temperature, is 100°F (37.8°C) on the lefthand side and 140°F (60°C) on the righthand side. Figure 2 shows the increased heat flow between the attic and the duct, as well as between the attic and the interior, when the attic temperature increases. Since the surface temperature of the duct is lower than the temperature of the interior, the temperature gradient between the interior and the attic is larger than the temperature gradient between the attic and the air inside the ducts when the attic temperature increases. The misalignment in temperature gradients indicates that less heat flows between the attic and the air inside the ducts compared to the total heat transfer from the attic. Therefore, the effective thermal resistance between the attic and the duct increases when the attic temperature increases. The increase in effective thermal resistance in the insulation is equivalent to an increase in the effective R-value of the buried ducts.

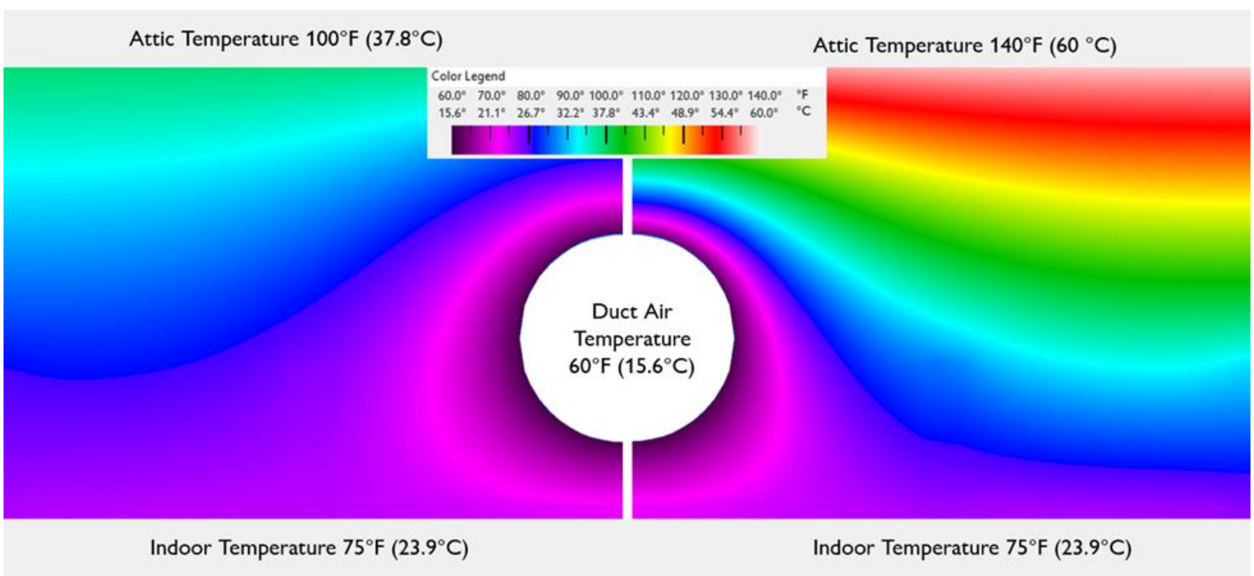

Figure 2: Temperature distributions inside the attic insulation under two different attic conditions.

2.2 Method

In Equation (1), the effective R-value of buried ducts is calculated using the inner surface area of the ducts, the temperature gradient between the attic and the air inside the duct, and the heat flow between the duct and the attic. Since the inner surface area is constant, the effective R-value becomes a function of attic temperature and heat flow.

$$R_{eff} = \frac{A_{d,i} \cdot \Delta T_{a \to d}}{\left| Q_{a \to d} \right|} \tag{1}$$

Manual calculations of the effective R-value are not possible due to the complexity of the thermal heat transfer from three boundary conditions. In addition, the attic temperature typically varies largely during the day. In the summer, attic temperatures up to 130°F (54.4°C) are not uncommon (Zoeller, 2009), while attic temperatures tend to drop below that of the outdoor air during cold winter nights. Due to these variables and out of convenience, this paper presents Equation (2), a polynomial regression equation that estimates the effective R-value of buried ducts at a given attic temperature.

$$
\begin{aligned}
R_{eff} &= \frac{A}{1000} T_K^2 + B \cdot T_K + C \\
T_K &= \left(T_a - 32\right) \cdot \frac{5}{9} + 273.15 \\
&\left[R_{eff}^{SI} \approx \frac{R_{eff}^{IP}}{5.6783} \right]
\end{aligned}
\tag{2}
$$

In this given equation, T_a is the attic temperature (°F) and R_{eff} is effective R-value (hr·ft^2·°F/Btu). Constants A, B, and C depend on the following characteristics:

- Duct insulation
- Inner duct diameter
- Attic insulation R-value
- Running mode (heating or cooling)

Equation (2) and associated constants A, B, and C are developed from thousands of simulation results utilizing THERM software, which is a two-dimensional steady-state heat transfer software (LBNL, 2023). Table 1 presents constants based on R-8 (R-1.4) duct insulation and ducts resting on ceiling drywall. Constants are shown for a range of attic insulation levels and varying duct diameters and are given for when the HVAC system is running in heating mode and in cooling mode. The regression equation using the constants in Table 1 has an R-squared value of 0.999 compared to THERM simulated effective R-values, indicating high accuracy.

Table 1: Effective R-value equation constants assuming R-8 (R-1.4) ducts resting on ceiling drywall.

		Attic Insulation [hr·ft²·°F/Btu (m²·K/W)]	Duct Diameter													
			4" (0.10 m)	5" (0.13 m)	6" (0.15 m)	7" (0.18 m)	8" (0.20 m)	9" (0.23 m)	10" (0.25 m)	12" (0.30 m)	14" (0.36 m)	16" (0.41 m)	18" (0.46 m)	20" (0.51 m)	22" (0.56 m)	24" (0.61 m)
A	Heating	30 (5.3)	-3.281	-3.169	-2.916	16.001	-2.276	-2.113	-1.985	-1.786	-1.638	-1.518	-1.557	-1.338	-1.296	-1.203
		38 (6.7)	-4.386	-4.482	-4.417	-4.231	-3.940	-3.553	-3.087	-2.466	-2.159	-1.944	-1.974	-1.655	-1.595	-1.458
		44 (7.7)	-5.070	-5.279	-5.319	-5.270	-5.102	-4.844	-4.510	-3.590	-2.767	-2.386	-2.388	-1.945	-1.860	-1.677
		49 (8.6)	-5.557	-5.841	-5.978	-6.003	-5.936	-5.764	-5.542	-4.830	-3.821	-2.928	-2.863	-2.251	-2.132	-1.895
		60 (10.6)	-6.401	-6.825	-7.099	-7.319	-7.424	-7.449	-7.363	-7.035	-6.452	-5.618	-5.409	-3.390	-3.017	-2.547
	Cooling	30 (5.3)	-11.755	-10.930	-9.699	-8.111	-7.071	-6.429	-5.948	-5.224	-4.700	-4.293	-4.377	-3.700	-3.575	-3.275
		38 (6.7)	-17.134	-16.958	-16.187	-15.056	-13.586	-11.870	-9.942	-7.562	-6.430	-5.678	-5.708	-4.689	-4.501	-4.049
		44 (7.7)	-20.829	-21.025	-20.676	-19.883	-18.779	-17.362	-15.703	-11.738	-8.550	-7.163	-7.088	-5.622	-5.357	-4.732
		49 (8.6)	-23.636	-24.253	-24.127	-23.689	-22.831	-21.661	-20.248	-16.768	-12.480	-9.072	-8.738	-6.632	-6.251	-5.417
		60 (10.6)	-28.943	-30.403	-30.929	-31.067	-30.786	-30.220	-29.374	-26.910	-23.653	-19.639	-18.422	-10.589	-9.353	-7.558
B	Heating	30 (5.3)	1.503	1.471	1.370	-9.148	1.090	1.017	0.959	0.867	0.798	0.742	0.762	0.657	0.637	0.592
		38 (6.7)	1.927	2.003	2.002	1.942	1.829	1.667	1.464	1.185	1.044	0.944	0.960	0.809	0.780	0.715
		44 (7.7)	2.158	2.290	2.343	2.356	2.309	2.217	2.087	1.695	1.326	1.152	1.156	0.947	0.906	0.820
		49 (8.6)	2.303	2.470	2.573	2.623	2.630	2.584	2.514	2.237	1.805	1.403	1.377	1.091	1.034	0.924
		60 (10.6)	2.490	2.720	2.888	3.039	3.136	3.195	3.196	3.125	2.925	2.596	2.522	1.621	1.445	1.233
	Cooling	30 (5.3)	7.890	7.311	6.465	5.390	4.688	4.257	3.934	3.450	3.100	2.829	2.884	2.436	2.353	2.154
		38 (6.7)	11.627	11.458	10.898	10.102	9.087	7.916	6.610	5.009	4.251	3.749	3.767	3.091	2.966	2.666
		44 (7.7)	14.245	14.316	14.022	13.435	12.646	11.656	10.512	7.813	5.667	4.739	4.686	3.710	3.534	3.118
		49 (8.6)	16.271	16.611	16.460	16.096	15.460	14.621	13.628	11.222	8.307	6.014	5.786	4.382	4.129	3.573
		60 (10.6)	20.215	21.105	21.371	21.372	21.098	20.635	19.993	18.210	15.920	13.151	12.307	7.024	6.200	4.996
C	Heating	30 (5.3)	-136.49	-137.17	-130.36	1328.39	-105.89	-99.10	-93.45	-84.33	-77.32	-71.44	-73.17	-62.47	-60.35	-55.50
		38 (6.7)	-158.87	-172.44	-178.07	-177.27	-170.65	-158.26	-141.06	-115.33	-101.78	-91.82	-93.24	-78.00	-75.05	-68.18
		44 (7.7)	-162.93	-182.69	-194.68	-203.05	-204.76	-201.34	-193.45	-162.39	-129.02	-112.29	-112.61	-91.82	-87.80	-78.88
		49 (8.6)	-159.23	-182.71	-200.53	-213.36	-221.88	-224.22	-224.16	-207.83	-172.95	-136.40	-134.09	-106.21	-100.65	-89.39
		60 (10.6)	-132.51	-161.73	-186.46	-211.65	-231.05	-246.65	-255.31	-265.30	-260.39	-240.06	-236.94	-157.37	-140.52	-120.12
	Cooling	30 (5.3)	-1284.0	-1184.8	-1043.2	-865.7	-750.2	-679.4	-626.3	-547.1	-489.9	-445.7	-453.6	-381.6	-368.3	-335.9
		38 (6.7)	-1912.3	-1876.9	-1778.8	-1643.0	-1472.7	-1278.1	-1062.8	-800.3	-676.3	-594.3	-596.2	-487.1	-467.1	-418.1
		44 (7.7)	-2358.7	-2361.5	-2304.6	-2200.9	-2064.8	-1897.2	-1705.5	-1258.4	-906.5	-754.7	-744.9	-587.1	-558.8	-490.9
		49 (8.6)	-2708.4	-2754.0	-2719.6	-2650.4	-2537.7	-2392.9	-2223.9	-1820.1	-1338.0	-962.0	-923.6	-695.7	-655.0	-564.1
		60 (10.6)	-3402.9	-3536.3	-3567.9	-3555.7	-3499.1	-3412.2	-3296.9	-2987.2	-2598.0	-2134.5	-1991.7	-1125.0	-991.9	-794.2

3. ANALYSIS OF EFFECTIVE R-VALUE

Extreme attic temperatures have a sizeable effect on the effective R-value of buried ducts in the attic. To show the impact of different climates and locations on the effective R-value, the polynomial regression equation presented in this paper was used together with simulated attic temperatures in several cities in the United States. A California Title 24 prescriptive standard 2,100 ft^2 (195 m^2) single family home was modeled using California's Building Energy Code Compliance Software, CBECC-Res (CBECC-Res, 2022). Hourly attic temperatures (°F), heating usage (kBtu), and cooling usage (kWh) were outputs of the simulation models. The maximum attic temperature in the modeling results was 137.3°F (58.5°C) seen in the climate of Harrisburg, PA, and the lowest attic temperature was -17.8°F (-27.7°C) for the model in Fargo, ND, indicating a large span in attic temperature depending on climate conditions.

The hourly attic temperature data from CBECC-Res was used to calculate hourly varying effective R-values for each climate using Equation (2) and the constants in Table 1. To analyze the impact of climate conditions, an R-8 (R-1.4) duct was assumed to be fully buried inside R-49 (R-8.6) fiberglass attic insulation and resting directly on top of ceiling drywall.

A weighted average effective R-value is calculated as presented in Equation (3):

$$\bar{R}_{eff} = \frac{\sum_{h=1}^{8760} R^c_{eff}(h) \cdot Q_c(h)}{\sum Q_c(h)} \varphi_c + \frac{\sum_{h=1}^{8760} R^h_{eff}(h) \cdot Q_h(h)}{\sum Q_h(h)} \varphi_h \quad (3)$$

The variables R^c_{eff} and R^h_{eff} are hourly effective R-values based on attic temperature during either cooling or heating. From simulations, the energy required for cooling, Q_c, and heating, Q_h, is used to weigh the relevance of each hourly effective R-value on the overall average, $\bar{R}_{eff}$. In Equation (3), the weighted values are summed for the entire year and divided by total energy use for cooling and heating. A final weighted average is calculated using the ratio of hours requiring cooling, φ_c, and heating, φ_h. The resulting average effective R-values for the simulated climates can be seen in Table 2.

Table 2: Weighted average effective R-values of an R-8 (R-1.4) buried duct in different U.S. climates. The duct is assumed fully buried inside R-49 (R-8.6) fiberglass attic insulation and resting directly on top of ceiling drywall.

Location	Average Heating Effective R-value, $\bar{R}^h_{eff}$ hr·ft²·°F/Btu (m²·K/W)	Hours with Heating	Average Cooling Effective R-value, $\bar{R}^c_{eff}$ hr·ft²·°F/Btu (m²·K/W)	Hours with Cooling	**Weighted Average Effective R-value,** $\bar{R}_{eff}$ **hr·ft²·°F/Btu (m²·K/W)**
Albany, NY	52.8 (9.3)	4323	65.1 (11.5)	121	**53.2 (9.4)**
Albuquerque, NM	47.7 (8.4)	3863	55.9 (9.8)	844	**49.2 (8.7)**
Anchorage, AK	54.0 (9.5)	6847	0.0 (0.0)	0	**54.0 (9.5)**
Athens, GA	49.9 (8.8)	2250	63.6 (11.2)	1874	**56.1 (9.9)**
Atlantic City, NJ	49.6 (8.7)	4529	53.3 (9.4)	255	**49.8 (8.8)**
Baltimore, MD	49.6 (8.7)	4366	53.7 (9.4)	847	**50.2 (8.8)**
Bangor, ME	50.7 (8.9)	5111	65.3 (11.5)	40	**50.8 (8.9)**
Boise, ID	51.2 (9.0)	2123	54.2 (9.5)	2160	**52.7 (9.3)**
Boston, MA	51.2 (9.0)	3614	54.6 (9.6)	520	**51.6 (9.1)**
Burlington, VT	50.2 (8.8)	4124	53.2 (9.4)	210	**50.3 (8.9)**
Birmingham, AL	47.6 (8.4)	2544	52.1 (9.2)	1745	**49.4 (8.7)**
Charleston, SC	49.9 (8.8)	1442	61.4 (10.8)	2646	**57.4 (10.1)**
Charleston, WV	49.4 (8.7)	4082	54.8 (9.6)	532	**50.0 (8.8)**
Cheyenne, WY	50.4 (8.9)	5937	0.0 (0.0)	0	**50.4 (8.9)**
Chicago, IL	53.0 (9.3)	4091	63.1 (11.1)	319	**53.7 (9.4)**
Cleveland, OH	52.4 (9.2)	4017	63.1 (11.1)	396	**53.3 (9.4)**
Denver, CO	51.4 (9.0)	3902	66.8 (11.8)	515	**53.2 (9.4)**
Des Moines, IA	53.6 (9.4)	3965	63.0 (11.1)	796	**55.2 (9.7)**
Detroit, MI	52.8 (9.3)	4234	63.3 (11.1)	282	**53.4 (9.4)**
Dover, DE	51.3 (9.0)	3490	64.0 (11.3)	646	**53.3 (9.4)**
Fargo, ND	56.3 (9.9)	4909	65.0 (11.4)	9	**56.3 (9.9)**
Harrisburg, PA	52.6 (9.3)	3967	64.2 (11.3)	776	**54.5 (9.6)**
Honolulu, HI	0.0 (0.0)	0	57.7 (10.2)	6731	**57.7 (10.2)**
Indianapolis, IN	53.1 (9.3)	3607	63.5 (11.2)	756	**54.9 (9.7)**
Jackson, MS	49.9 (8.8)	1850	63.0 (11.1)	2435	**57.4 (10.1)**
Kansas City, MO	51.1 (9.0)	4369	54.0 (9.5)	753	**51.5 (9.1)**
Las Vegas, NV	48.9 (8.6)	1504	65.0 (11.4)	3283	**59.9 (10.6)**
Little Rock, AR	50.9 (9.0)	2586	63.8 (11.2)	2355	**57.1 (10.0)**
Los Angeles, CA	45.7 (8.0)	648	0.0 (0.0)	0	**45.7 (8.0)**
Louisville, KY	49.9 (8.8)	3921	54.2 (9.5)	1066	**50.8 (8.9)**

Manchester, NH	51.9 (9.1)	4420	65.2 (11.5)	302	**52.8 (9.3)**
Miami, FL	0.0 (0.0)	0	58.3 (10.3)	5757	**58.3 (10.3)**
Milwaukee, WI	52.9 (9.3)	4852	65.6 (11.6)	24	**53.0 (9.3)**
Minneapolis, MN	54.2 (9.5)	4722	64.4 (11.3)	137	**54.4 (9.6)**
Missoula, MT	51.6 (9.1)	5040	62.5 (11.0)	8	**51.6 (9.1)**
Nashville, TN	48.9 (8.6)	3420	54.2 (9.5)	1575	**50.6 (8.9)**
New Haven, CT	50.8 (8.9)	4145	63.1 (11.1)	308	**51.6 (9.1)**
New Orleans, LA	48.7 (8.6)	773	61.2 (10.8)	3255	**58.8 (10.3)**
Oklahoma City, OK	51.4 (9.0)	3195	64.3 (11.3)	2168	**56.6 (10.0)**
Omaha, NE	54.1 (9.5)	3737	64.4 (11.3)	910	**56.1 (9.9)**
Pawtucket, RI	51.8 (9.1)	4500	66.4 (11.7)	119	**52.2 (9.2)**
Phoenix, AZ	48.8 (8.6)	195	67.6 (11.9)	4250	**66.8 (11.8)**
Portland, OR	46.8 (8.2)	4987	54.8 (9.6)	2	**46.8 (8.2)**
Raleigh, NC	48.0 (8.4)	3387	54.1 (9.5)	1192	**49.6 (8.7)**
Rapid City, SD	53.1 (9.3)	4940	65.9 (11.6)	109	**53.4 (9.4)**
Richmond, VA	48.6 (8.5)	3695	54.2 (9.5)	1076	**49.8 (8.8)**
Salt Lake City, UT	50.8 (8.9)	3609	64.9 (11.4)	1095	**54.1 (9.5)**
San Antonio, TX	48.9 (8.6)	791	63.8 (11.2)	3186	**60.8 (10.7)**
Seattle, WA	47.0 (8.3)	5603	0.0 (0.0)	0	**47.0 (8.3)**
Topeka, KS	50.2 (8.8)	4061	54.7 (9.6)	717	**50.9 (9.0)**

The weighted average effective R-values in Table 2 range from 45.7 (8.0) to 66.8 (11.8), with the maximum value in Phoenix, AZ, and the minimum value in Los Angeles, CA. Notably, Los Angeles, Seattle, and Portland have the lowest number of cooling hours, and these cities have the lowest effective R-values. Anchorage, AK, and Cheynne, WY, both have zero cooling hours, but they are in climates with lower outdoor temperatures during the heating season, which leads to a larger effective R-value than other climates that see fewer extreme temperatures.
Figure 3 shows the distribution of the effective R-value versus the number of hours the system is running in cooling, fitted with a trendline that omits the two outliers. This figure shows that the weighted average effective R-value typically increases with the number of cooling hours, i.e., the cooling demand. The two outliers on the far right represent Miami, FL, and Honolulu, HI, which have the most cooling hours; however, the maximum attic temperatures are not among the highest seen, at 119.1°F (48.4°C) and 119.8°F (48.8°C), respectively. The city with the highest effective R-value is Phoenix, AZ, which has a higher maximum attic temperature of 133.6°F (56.4°C). The distribution of the weighted effective R-value is similar for heating hours but rather decreases with an increased number of hours.

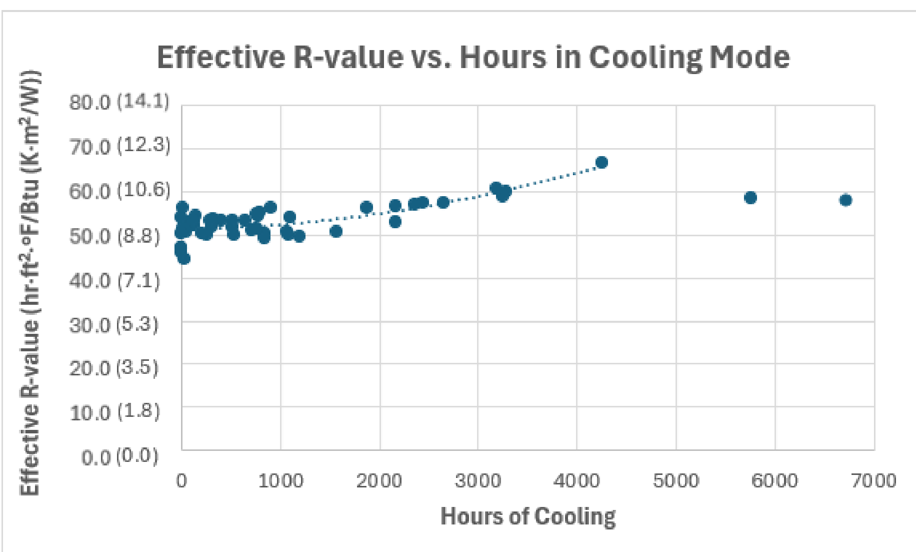

Figure 3: Effective R-value of each city versus cooling hours.

Another takeaway from these results is the impact of heating mode versus cooling mode on the effective R-value. The range of the heating average effective R-value is 45.7 (8.0) to 56.3 (9.9), not counting the cities where it is zero because there is no heating load. The range for the cooling effective R-value is 52.1 (9.2) to 67.6 (11.9), not counting cities with no cooling load. The cooling effective R-values are overall greater, which shows the increase in overall effective R-value with the number of hours a system runs in cooling mode. When the system is running in cooling mode, attic temperatures are the highest; therefore, higher attic temperatures are seen to be linked with higher effective R-values. Looking at the results, it can be said that climate affects the overall effective R-value. Cooling-dominated climates see the highest outdoor temperatures and, therefore, the highest attic temperatures and effective R-values. In other words, climates with a higher cooling demand benefit more from buried ducts for HVAC distribution system energy losses.

4. DISCUSSION

The benefits of burying ducts are evident given the effective R-value results. Typical ducts in the attic are suspended from the ceiling and only have jacket insulation, which is typically R-6 (R-1.4) or R-8 (R-1.1). In 2006, Palmiter showed that the true R-value of ductwork is less than its nominal value (Palmiter & Kruse, 2006). For example, Palmiter found that a 6” (152 mm) diameter duct with R-8 (R-1.4) nominal insulation has an actual total R-value of 6.45 (1.14) including surface film resistance. Taking this into account, the benefit of having ducts buried in attic insulation is even greater. This paper only shows results for when ducts are buried and resting on the ceiling, but there are great benefits from buried ducts that rest on the ceiling trusses and even on top of insulation. The closer the ducts are to the indoor space, the less energy loss there is between the ducts and the attic. When the ducts rest on the ceiling drywall, there is more insulation on top of the ducts and therefore a larger thermal resistance between the ducts and the attic.

Additionally, when ducts are buried in attic insulation, there is an expected increase in the service life of the buried ducts as they are not exposed to the same extreme attic temperatures that suspended ducts are. In 2005, Walker and Sherman tested the performance of duct tapes and sealants when the ducts were exposed to high temperatures. Multiple different types of sealants were tested, and the results showed that higher temperatures were most likely to result in sealant failures (Walker & Sherman, 2005). Therefore, having ducts buried in attic insulation will protect them from the extreme attic temperatures and help prolong the lifetime of the ducts.

Another benefit of buried ducts is the likelihood that a smaller system is needed. Burying ducts in attic insulation can be comparable to having the system ductwork inside conditioned space. A high effective R-value for the attic ducts means significantly less heat is exchanged with the surrounding environment, and the efficiency of the HVAC system increases. When a system is more energy efficient, it requires a lower capacity unit to condition a space with the same load, as there are fewer energy losses within the distribution system. For example, a contractor in northern California has shared that he was able to decrease the air conditioning unit size from 5 to 3 tons in a home with the addition of deeply buried ducts alone.

5. BARRIERS TO IMPLEMENTATION

The idea of burying ducts in attic insulation has been around for several years but is not commonly seen in practice compared to suspended ducts. Installing buried ducts in an attic has minimal technical feasibility constraints and the materials needed to bury ducts are already used in construction. However, realizing energy savings from burying ducts and seeing the full benefit relies on proper installation. Reducing the real and perceived barriers related to cost and level of difficulty is necessary to see buried ducts become common practice.

Designing a fully buried duct system for a building retrofit requires knowing the current insulation level and the largest duct size. Manufacturer coverage tables for loose fill insulation may be a higher R-value per inch and therefore requires less coverage to achieve the same R-value. The installer’s certificate of installation requires the installation depth as well as the R-value to be recorded, and a depth may be required that exceeds the targeted R-value for the ceiling assembly. Installing appropriate levels of insulation in attics with complicated ceiling designs, such as dropped ceilings, can be challenging. In addition, there can be scenarios where a mix of buried and unburied ducts is required, such as rooms with cathedral ceilings. Having adequate distribution of attic insulation is essential to seeing the greatest benefit from buried ducts.

One area of concern that has been addressed in previous buried duct work is the risk of moisture and condensation. Salonvaara et al. (2016) analyzed buried ducts in Cleveland, OH, which is in IECC climate zone 5A, and Charleston, SC, located in climate zone 3A (Salonvaara et al., 2016). In a lab test simulating worst-case condensation conditions in Charleston, a hot and humid climate, visible moisture was observed on some areas of the flex duct surface; however, no dripping onto the drywall was observed. Field testing performed in Cleveland did not show any signs of condensation or moisture. It was concluded that using R-8 (R-1.4) ducts is critical in some climates, and for drier climates, like Cleveland, the risk for condensation is low. The benefit of buried ducts increases with decreased duct jacket insulation. In other words, an R-6 buried duct will have a higher effective R-value compared to an R-8 (R-1.4). However, the risk of condensation on the exterior side of the duct insulation increases slightly with R-6 (R-1.1), which may require R-8 (R-1.4) in hot and humid climates.

Verification of duct burial has proven to be a large market barrier. Even though measuring sticks can verify the thickness of attic insulation, the amount of insulation on top of the ducts is more difficult to verify. This becomes an issue for deeply buried ducts, which require at least 3.5 inches (0.09 m) on top of the ducts. To estimate the performance of buried ducts, compliance software requires detailed duct design information, including duct diameters, lengths, duct insulation, and type of attic insulation. Additionally, a Certificate of Compliance requires a scaled drawing showing the locations of equipment, including supply and return grilles, duct sizes and R-values, and the location of each duct, among other details. Duct design must be based on ACCA Manual D or equivalent. All ducts that are fully buried are required to have vertical markers placed every eight feet. The upsides of a proper duct design are an expected longer service life of the HVAC system, and with buried ducts, a need for a lower HVAC system capacity due to fewer duct distribution energy losses.

6. CONCLUSIONS

This paper presents a methodology for calculating the effective R-value of buried ducts, which has previously been underestimated. The effective R-value depends on multiple factors, including duct diameter, duct insulation value, attic insulation level and material, and, more controversially, the temperature boundary conditions.

The effective R-value of buried ducts is proven to be strongly dependent on the attic temperature. More specifically, the effective R-value of buried ducts increases with increasing attic temperatures. Consequently, this paper shows that the effective R-value tends to be higher in cooling-dominated climates due to a higher attic temperature in climates with higher solar loads.

Unfortunately, there is still a relatively low adoption rate for buried ducts, despite a performance like that of ducts inside conditioned space. The reasons for market barriers include the perceived risk of condensation and compliance verification. The path to compliance and enforcement would benefit from further elaboration, which would help increase market penetration.

REFERENCES

CalCERTS. (2023, January). Confidential Data Request from CalCERTS. Folsom, CA.
CBECC-Res. (2022). California Building Energy Code Compliance software.
Griffiths, D., & Zuluaga, M. (2004). An Analysis of the Effective R-Value for Insulation Buried Attic Ducts. *ASHRAE Transactions*, 6.
Griffiths, D., Aldrich, R., Zoeller, W., & Zuluaga, M. (2002). An Innovative Approach to Reducing Duct Heat Gains for a Prodcution Builder in a Hot and Humid Climate - How We Got There. *Panel 1.2002 ACEEE Summer Study - Residential Buildigns: Technologies, Design, Performance Analysis, and Building Industry Trends* (p. 10). ACEEE.
HIRL. (2016). *Compact Buried Ducts in a Hot-Humid Climate House.* Lady's Island, SC: Building America Case Study under Building Technologies Office.
LBNL. (2023). THERM - Two-Dimensional Building Heat-Transfer Modeling Software. Berkeley, CA.
Mallay, D. (2016). *Compact Buried Ducts in a Hot-Humid Climate House.* Denver: U.S. Department of Energy .
Palmiter, L., & Kruse, E. (2006). True R-Values of Round Residential Ductwork. *ACEEE Summer Study on Energy Efficiency in Buildings* (pp. 199-210). Monetrey, CA: ACEEE.

Salonvaara, M., Karagiozis, A., Friedberg, N., & Salonvaara, K. (2019). Buried Ducts: A Cost-Effective Technical Solution to High Performance Homes. *Buildings Conference XIV* (p. 10). Clearwater, FL: ASHRAE.
Salonvaara, M., Keeley, K., & Karagiozis, A. (2016). Thermal and Moisture Performance of Buried Ducts. *Buildings XIII.* Clearwater, FL.
Shapiro, C. (2013). *Encapsulated and Buried Ducts.* Norwalk, CT: Consortium for Advanced Residential Buildings, Steven Winter Associates, Inc.
Shapiro, C., Zoeller, W., & Mantha, P. (2013). *Measured Guideline: Buried and/or Encapsulated Ducts.* Denver: U.S. Department of Energy.
Shaprio, C., Magee, A., & Zoeller, W. (2013). *Reducing Thermal Losses and Gains with Buried and Encapsulated Ducts in Hot-Humid Climates.* Denver, CO: U.S. Department of Energy.
Walker, I. S., & Sherman, M. H. (2005). *Duct Tape and Sealant Performance.* LBNL.
Zoeller, W. (2009). *Still Placing Ducts in the Attic? Consider Burying Them.* Norwalk, CT: Consortium for Advanced Residential Buildings, Steven Winter Associates, Inc.