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Calculations for Reflective Roofs in Support of Standard 90.1

Hashem Akbari, Ph.D.
Member ASHRAE

Steven J. Konopacki

Charles N. Eley, P.E.
Member ASHRAE

Bruce A. Wilcox, P.E.
Member ASHRAE

Martha G. Van Geem, P.E.
Member ASHRAE

Danny S. Parker
Associate Member ASHRAE

ABSTRACT

This paper summarizes the results of a simulation effort in support of ASHRAE SSPC 90.1 for the inclusion of reflective roofs in the proposed standard. Simulation results include the annual electricity and fuel use for two buildings types, residential and nonresidential. The residential model is intended to apply to hotel guest rooms, patient rooms in hospitals, and high-rise residential apartments. In order to be consistent with other requirements of the draft standard, we used the 90.1 Envelope Subcommittee DOE-2 prototype building and operating schedules, which were supplied to us. The parametric simulations were performed for 19 climate bins, as defined in the current 90.1 draft (a total of 26 climate bins are used in 90.1, while only 19 are considered in this study); a range of roof absorptivities from 0.25 to 0.95; and three roof U-factors (corresponding to roof insulation of R3, R11, and R38). The results are condensed into climate-dependent adjustment factors to reduce roof insulation for buildings with reflective roofs such that the net energy use of the building stays constant when compared with the energy use of a dark-colored roof.

INTRODUCTION

Most commercial and residential buildings have dark roofs. Dark roofs are heated by the summer sun, which raises the summertime cooling demand. For highly absorptive (low-solar reflectance) roofs, the difference between the surface and ambient air temperatures may be as high as 50°C (90°F), while for less absorptive (high-solar reflectance) roofs, such as those painted white, the difference is only about 10°C (18°F). For this reason, "cool" roofs (which absorb little "insolation") are effective in reducing cooling energy use. Numerous experiments in several residential and small commercial buildings in California and Florida show that painting roofs white reduces air-conditioning energy use (the compressor and condenser unit) between 10% and 50% (savings from $10 to $100 per year per 100 m^2), depending on the amount of thermal resistance of insulation under the roof (Akbari et al. 1997; Parker et al. 1995). The savings, of course, are strong functions of the thermal integrity of a building and climatic conditions. The Envelope Subcommittee of ASHRAE Standing Standard Project Committee 90.1 has recognized the importance of the reflectivity of the roof of high-rise buildings in reducing the net energy consumption of a building. In order to be consistent with other sections of the proposed standard, they required simulations of building heating and cooling energy use of two prototypical buildings over a wide range of climates. This paper summarizes the results of a simulation effort in support of ASHRAE SSPC 90.1 for the inclusion of reflective roofs in the proposed standard.

METHODOLOGY

Reflective roofs reduce the inflow of heat into a building by reflecting most of the incident solar radiation during hot summer days. Having a well-insulated roof will also reduce the heat gains during the day. During those hours of the day when the ambient temperature is lower than the inside temperature, having high insulation in the roof would block the path of heat flow out of the building. During the winter, when the days are short and cloudy and the sun angle is low, a reflective roof may add a heating penalty. Therefore, we analyzed the impact of the roof reflectance in terms of a trade-off with roof insulation. On that basis, the Envelope Subcommittee directed us to perform comprehensive simulations to analyze cooling energy savings and heating energy penalties of two prototypical buildings over a wide spectrum of climatic conditions. The DOE-2.1E building energy simulation program was selected as the tool to perform this analysis. DOE-2 was devel-

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Hashem Akbari is a staff scientist and **Steven J. Konopacki** is a principal research associate, Lawrence Berkeley National Laboratory, Berkeley, Calif. **Charles N. Eley** is president, Eley Associates, San Francisco, Calif. **Bruce A. Wilcox** is president, Berkeley Solar Group, Oakland, Calif. **Martha G. Van Geem** is a principal engineer, Construction Tech Laboratories, Inc., Skokie, Ill. **Danny S. Parker** is a principal research scientist, Florida Solar Energy Center, Cocoa, Fla.

oped by the U.S. Department of Energy and has been widely accepted as a useful tool for calculating building heating and cooling energy use and sizing of HVAC equipment. We used two building prototypes for this analysis: a residential and a nonresidential building. The residential model is intended to apply to hotel guest rooms, patient rooms in hospitals, and high-rise residential apartments. These prototypes have been used extensively in support of developing criteria for Standard 90.1. For a detailed description of these prototypes, see Eley and Kolderup (1992). The buildings were simulated with electric cooling and gas heating systems. These buildings were simulated for a variety of roof insulation and roof reflectances. The roof insulations included low (R3), medium (R11), and high (R38) values. The roof components included a 3/8 in. built-up roof, 3/4 in. plywood, insulation, and 5/8 in. gypsum board. Parameters for roof reflectivity included reflectances of 0.05, 0.15, 0.45, and 0.75. As discussed later, there was a linear relationship between building energy use and roof reflectance. So the parametric intervals selected for roof reflectance were sufficient. The simulations were performed for a wide range of climatic conditions, from very hot to very cold. A total of 26 climate bins are used in 90.1, while only 19 are considered in this study. The other seven consist of cold climatic conditions where light-colored roofs are not recommended. These climatic conditions are shown in Table 1. Upon completion of simulated heating and cooling energy use, we regressed the results into linear functions of roof absorptance (1 - reflectance), a, and U-factor, U, of the roof. The equation used is

$$E_i = C_0 + C_1 a + C_2 U + C_3 U a, \qquad (1)$$

where, E_i is either annual electricity use in kWh, annual gas energy use in therms, or net energy use in dollars. This linear correlation proved to be adequate for our analysis. To obtain the net energy-use cost, we used $0.08/kWH and $0.66/therm for the price of electricity and gas,[1] respectively. The $0.66/therm represents a weighted average cost of providing heating, including gas heating, electric heat pump heating, and electric resistance heating prior to applying an efficiency adjustment and is used to develop envelope criteria only.

TABLE 1
Cooling and Heating Degree Days for the Simulated Climates

Location	CDD (Base 50)	HDD (Base 65)	Bin
Honolulu	9804	0	2
Miami	9261	227	2
Tampa	8022	604	3
Phoenix	7858	1356	5
Lake Charles	6860	1535	6
San Diego	5170	1076	7
Fort Worth	6200	2376	8
San Bernardino	4854	2103	9
Atlanta	4922	3022	11
San Francisco	2486	3238	12
Amarillo	4262	4226	13
Portland	2320	4626	14
Seattle	1716	5222	15
Boise	2748	5918	17
Vancouver	1468	5738	18
Minneapolis	2701	8112	19
Halifax	1447	7828	20
Bismarck	2222	9056	21
Anchorage	684	10371	22
Edmonton	880	11270	23

SOLAR REFLECTANCE OF ROOFING MATERIALS

LBNL and FSEC have collected and compiled data on the solar reflectance of roofing materials. These data can be grouped in the following categories: asphalt shingles, white roof coatings (white, tinted, and aluminum), roofing membranes, metal roofing, tiles, and miscellaneous roofs. The solar reflectance of most existing asphalt shingles ranges from 0.03 to 0.26, with the majority ranging from 0.10 to 0.15 (HIG 1997). Roofing membranes such as black single-ply roofing, smooth bitumen, gray single-ply roofing, and white granular surface bitumen have reflectivities of 0.06, 0.06, 0.23, and 0.26, respectively. Metal roofs can have higher reflectance (about 0.60), but because of a low thermal emittance, they get as hot as dark roofs. Gravel roofs, depending on the color of the gravel, have reflectances of about 0.12 to 0.34. Based on these data, a base-case (dark) albedo of 0.20 is fairly conservative and is recommended for this study.

The roof reflectance can be improved either by roofing material that is reflective or by using reflective coatings. Freshly applied white coatings have a solar reflectance in the range of 0.60 to 0.85. Our data for aluminum-based coatings indicate a solar reflectance in the range of 0.30 to 0.61. Some manufacturers claim that their coatings have higher solar reflectance and their reflectivities last longer than white coatings. With regard to aging and weathering of coatings, we have observed a decrease of about 10% to 15% in the solar reflectance in the first few months of applications and no further decrease later on. White single-ply roofings have very high solar reflectances (greater than 0.7), which are typically decreased by 10% to 15% because of weathering. For these calculations, we assumed that the roofing surface should have an initial reflectivity greater than 0.70 with a thermal emissivity of > 0.80, but the benefits of the reflective roof were simu-

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[1] The national average cost of gas is $0.56/therm. The $0.66 is inflated by a multiplier of 1.17 to include an assumption of 10% electric resistance heat.

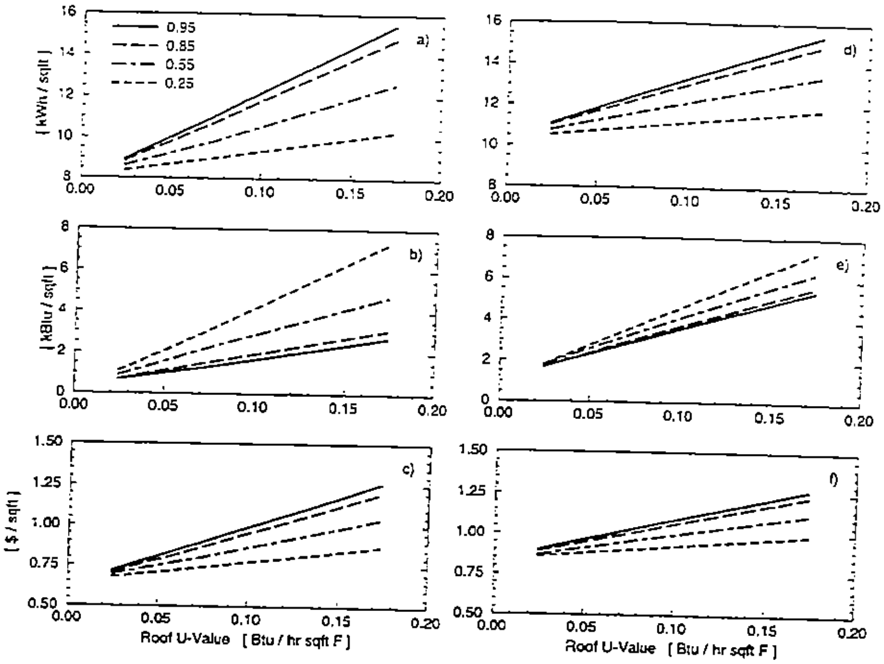

Figure 1 *DOE-2 simulated total annual energy use for prototypical buildings with roof absorptance values of 0.95, 0.85, 0.55, and 0.25, using Phoenix TMY2 weather data. Residential building: a) annual electricity use, b) annual gas use, and c) annual net energy use; nonresidential building: d) annual electricity use, e) annual gas use, and f) annual net energy use. Net energy use is calculated with \$0.08/kWh for electricity and \$0.66/therm for gas.*

lated with the reflectance of 0.55 to account for the effects of weathering and direct collection.

RESULTS

Tables 2 and 3 show the total annual electricity and gas use for the prototypical buildings. The annual electricity, gas, and total energy use for the two prototypes for Phoenix is shown in Figure 1. The graphs suggest a strong linear correlation between energy use and roof U-factor (and roof absorptance, not shown in Figure 1).

We regressed the simulation results using the linear relationship described in Equation 1; the combined coefficient for heating and cooling energy use presented in dollar terms is shown in Table 4. The R^2 for regressions for both heating and cooling energy use were better than 0.99 for most cases. Other regression statistics showed a high degree of linear correlation between building energy use, roof U-factor, and roof absorptivity. For the rest of this analysis, we used these regression correlations. Note that the value of the term $C_1 a$ is small relative to the other terms in the correlation.

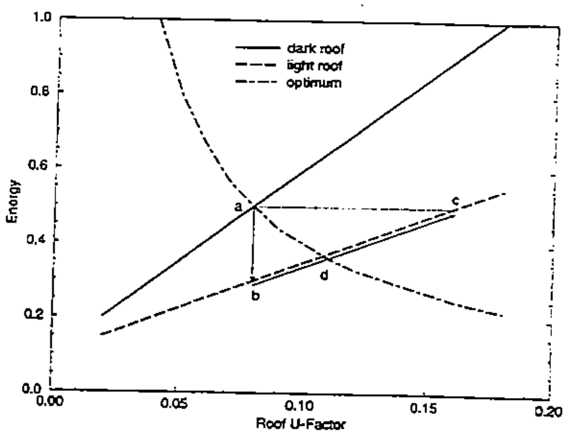

Figure 2 *Selection of the optimum roof U-factor for a given roof absorptance.*

We combined electricity and gas regressions to calculate the net energy cost of operating the building. To calculate an equivalency between the roof absorptivity and roof insulation, an initial roof absorptivity of 0.80 was assumed. For a given roof U-factor (U_1), the net energy cost in the building was estimated, which is point "a" in Figure 2. Then the roof absorptivity was changed to 0.45. This resulted in a lower net energy cost, as shown by "b" in Figure 2. A new roof U-factor is then calculated for the case of reflective roofs, such that the energy use will be the same as the initial condition, point "c" in Figure 2. Having calculated the new roof U-factor (U_2), a U-factor = U_2/U_1 is defined. Ignoring $C_1 a$ in the regressions,

$$\frac{U_2}{U_1} = \frac{C_2 + C_3 a1}{C_2 + C_3 a2}\,. \tag{2}$$

TABLE 2
DOE-2 Simulated Total Annual Electricity Use for Residential and Nonresidential Buildings (kWh/ft^2)

Location/U-Factor	Residential Building				Nonresidential Building			
	Absorptivity				Absorptivity			
	0.95	0.85	0.55	0.25	0.95	0.85	0.55	0.25
Honolulu								
U = 0.0245	8.72	8.65	8.44	8.28	11.21	11.15	10.99	10.83
U = 0.0726	9.93	9.67	8.99	8.32	12.07	11.91	11.44	10.95
U = 0.1734	12.92	12.29	10.37	8.59	13.86	13.46	12.34	11.24
Miami								
U = 0.0245	8.91	8.83	8.60	8.41	11.24	11.19	11.01	10.83
U = 0.0726	10.27	10.02	9.28	8.57	12.24	12.07	11.55	11.00
U = 0.1734	13.63	12.99	11.04	9.05	14.27	13.88	12.67	11.42
Tampa								
U = 0.0245	7.99	7.92	7.65	7.52	10.55	10.50	10.32	10.17
U = 0.0726	9.14	8.91	8.32	7.67	11.43	11.28	10.81	10.33
U = 0.1734	12.03	11.48	9.81	8.18	13.22	12.86	11.81	10.73
Phoenix								
U = 0.0245	8.94	8.86	8.63	8.39	11.08	11.01	10.78	10.54
U = 0.0726	10.97	10.67	9.77	8.97	12.51	12.30	11.65	10.94
U = 0.1734	15.48	14.78	12.59	10.27	15.38	14.91	13.42	11.79
Lake Charles								
U = 0.0245	7.89	7.82	7.63	7.42	10.24	10.20	10.04	9.87
U = 0.0726	9.31	9.06	8.28	7.65	11.18	11.03	10.53	10.03
U = 0.1734	12.53	11.95	10.14	8.25	13.14	12.78	11.64	10.47
San Diego								
U = 0.0245	6.20	6.15	6.00	5.86	8.87	8.82	8.66	8.50
U = 0.0726	7.18	6.97	6.31	5.79	9.52	9.38	8.95	8.49
U = 0.1734	9.43	8.95	7.47	5.96	10.90	10.58	9.61	8.60
Fort Worth								
U = 0.0245	7.90	7.84	7.65	7.46	10.04	9.99	9.84	9.68
U = 0.0726	9.19	8.97	8.40	7.81	10.95	10.81	10.37	9.92
U = 0.1734	12.38	11.85	10.22	8.61	12.81	12.49	11.49	10.45
San Bernardino								
U = 0.0245	7.06	7.00	6.78	6.56	9.59	9.54	9.35	9.15
U = 0.0726	8.42	8.18	7.41	6.75	10.55	10.39	9.86	9.26
U = 0.1734	11.51	10.95	9.18	7.34	12.52	12.15	10.96	9.63
Atlanta								
U = 0.0245	6.88	6.81	6.61	6.42	9.29	9.24	9.08	8.92
U = 0.0726	7.99	7.78	7.18	6.54	10.08	9.94	9.50	9.01
U = 0.1734	10.70	10.17	8.54	6.94	11.68	11.35	10.33	9.26
San Francisco								
U = 0.0245	5.21	5.17	5.07	4.98	7.73	7.70	7.59	7.49
U = 0.0726	6.01	5.86	5.38	5.06	8.20	8.11	7.82	7.52
U = 0.1734	7.94	7.58	6.46	5.40	9.21	9.00	8.34	7.64

TABLE 2 (Continued)

DOE-2 Simulated Total Annual Electricity Use for Residential and Nonresidential Buildings (kWh/ft^2)

Location/U-Factor	Residential Building				Nonresidential Building			
	Absorptivity				Absorptivity			
	0.95	0.85	0.55	0.25	0.95	0.85	0.55	0.25
Amarillo								
U = 0.0245	6.91	6.85	6.66	6.47	9.07	9.03	8.90	8.76
U = 0.0726	8.08	7.87	7.29	6.70	9.86	9.72	9.29	8.88
U = 0.1734	11.08	10.56	8.91	7.28	11.53	11.20	10.20	9.23
Portland								
U = 0.0245	5.63	5.59	5.46	5.33	7.96	7.92	7.82	7.72
U = 0.0726	6.29	6.18	5.84	5.47	8.47	8.38	8.09	7.78
U = 0.1734	8.03	7.67	6.69	5.86	9.56	9.34	8.67	8.01
Seattle								
U = 0.0245	5.33	5.30	5.19	5.09	7.64	7.61	7.52	7.42
U = 0.0726	5.94	5.83	5.49	5.18	8.10	8.01	7.74	7.46
U =0.1734	7.53	7.21	6.25	5.44	9.07	8.87	8.24	7.62
Boise								
U = 0.0245	6.39	6.33	6.16	5.99	8.61	8.57	8.43	8.29
U = 0.0726	7.47	7.28	6.77	6.25	9.37	9.25	8.86	8.45
U = 0.1734	10.05	9.62	8.26	6.83	10.95	10.66	9.77	8.83
Vancouver								
U = 0.0245	5.26	5.22	5.10	4.98	7.53	7.50	7.40	7.31
U = 0.0726	5.82	5.70	5.34	4.96	7.94	7.85	7.57	7.28
U = 0.1734	7.26	6.92	5.91	5.25	8.81	8.61	7.98	7.32
Minneapolis								
U = 0.0245	6.01	5.97	5.86	5.75	8.33	8.29	8.19	8.08
U = 0.0726	6.78	6.62	6.26	6.03	8.88	8.78	8.47	8.16
U = 0.1734	8.03	7.66	6.52	5.72	9.28	9.05	8.36	7.62
Halifax								
U = 0.0245	5.38	5.35	5.24	5.13	7.70	7.66	7.56	7.46
U = 0.0726	6.11	5.95	5.52	5.19	8.18	8.09	7.80	7.49
U = 0.1734	8.03	7.66	6.52	5.72	9.28	9.05	8.36	7.62
Bismarck								
U = 0.0245	6.09	6.04	5.91	5.78	8.25	8.22	8.11	7.99
U = 0.0726	7.02	6.87	6.40	5.99	8.84	8.74	8.42	8.09
U = 0.1734	6.78	6.51	6.01	5.79	8.25	8.09	7.58	7.17
Anchorage								
U = 0.0245	5.12	5.09	5.00	4.91	7.20	7.17	7.10	7.02
U = 0.0726	5.63	5.54	5.27	5.17	7.54	7.47	7.26	7.03
U = 0.1734	6.78	6.51	6.01	5.79	8.25	8.09	7.58	7.17
Edmonton								
U = 0.0245	5.57	5.52	5.40	5.26	7.62	7.59	7.49	7.40
U = 0.0726	6.25	6.14	5.77	5.59	8.08	8.00	7.71	7.42
U = 0.1734	8.04	7.69	6.70	6.34	9.09	8.87	8.22	7.67

TABLE 3

DOE-2 Simulated Total Annual Natural Gas Use for Residential and Nonresidential Buildings (therms/ft^2)

Location/U-Factor	Residential Building				Nonresidential Building			
	Absorptivity				Absorptivity			
	0.95	0.85	0.55	0.25	0.95	0.85	0.55	0.25
Honolulu								
U = 0.0245	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
U = 0.0726	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
U = 0.1734	0.000	0.000	0.000	0.001	0.000	0.001	0.001	0.001
Miami								
U = 0.0245	0.001	0.001	0.001	0.001	0.002	0.002	0.002	0.002
U = 0.0726	0.002	0.002	0.003	0.004	0.004	0.004	0.004	0.005
U = 0.1734	0.004	0.005	0.007	0.011	0.009	0.009	0.010	0.012
Tampa								
U = 0.0245	0.006	0.006	0.007	0.007	0.007	0.007	0.008	0.008
U = 0.0726	0.010	0.011	0.013	0.017	0.014	0.014	0.016	0.017
U = 0.1734	0.018	0.021	0.029	0.041	0.029	0.030	0.033	0.038
Phoenix								
U = 0.0245	0.007	0.007	0.009	0.011	0.017	0.017	0.018	0.018
U = 0.0726	0.013	0.015	0.022	0.030	0.029	0.030	0.033	0.036
U = 0.1734	0.027	0.031	0.047	0.073	0.054	0.056	0.063	0.073
Lake Charles								
U = 0.0245	0.024	0.025	0.027	0.030	0.020	0.020	0.021	0.021
U = 0.0726	0.034	0.036	0.044	0.054	0.033	0.034	0.036	0.038
U = 0.1734	0.050	0.055	0.075	0.103	0.057	0.059	0.066	0.075
San Diego								
U = 0.0245	0.002	0.002	0.003	0.003	0.007	0.008	0.008	0.009
U = 0.0726	0.005	0.005	0.009	0.015	0.018	0.018	0.021	0.024
U = 0.1734	0.012	0.015	0.027	0.055	0.040	0.041	0.048	0.056
Fort Worth								
U = 0.0245	0.047	0.048	0.052	0.055	0.035	0.035	0.036	0.037
U = 0.0726	0.065	0.068	0.078	0.089	0.053	0.055	0.058	0.062
U = 0.1734	0.092	0.100	0.127	0.163	0.089	0.091	0.101	0.114
San Bernardino								
U = 0.0245	0.014	0.015	0.017	0.021	0.026	0.027	0.028	0.029
U = 0.0726	0.025	0.028	0.039	0.054	0.048	0.050	0.054	0.060
U = 0.1734	0.050	0.056	0.081	0.129	0.091	0.094	0.106	0.123
Atlanta								
U = 0.0245	0.068	0.070	0.074	0.078	0.046	0.047	0.048	0.050
U = 0.0726	0.093	0.097	0.110	0.126	0.072	0.073	0.079	0.085
U = 0.1734	0.136	0.145	0.180	0.224	0.120	0.124	0.139	0.156
San Francisco								
U = 0.0245	0.030	0.031	0.036	0.041	0.032	0.033	0.034	0.036
U = 0.0726	0.043	0.049	0.069	0.092	0.058	0.060	0.066	0.072
U = 0.1734	0.069	0.080	0.130	0.206	0.107	0.111	0.125	0.145

TABLE 3 (Continued)

DOE-2 Simulated Total Annual Natural Gas Use for Residential and Nonresidential Buildings (therms/ft^2)

Location/U-Factor	Residential Building				Nonresidential Building			
	Absorptivity				Absorptivity			
	0.95	**0.85**	**0.55**	**0.25**	**0.95**	**0.85**	**0.55**	**0.25**
Amarillo								
U = 0.0245	0.103	0.105	0.111	0.117	0.074	0.075	0.077	0.079
U = 0.0726	0.139	0.145	0.163	0.182	0.110	0.112	0.119	0.127
U = 0.1734	0.199	0.213	0.260	0.316	0.176	0.181	0.200	0.222
Portland								
U = 0.0245	0.116	0.118	0.123	0.130	0.067	0.067	0.070	0.072
U = 0.0726	0.161	0.166	0.182	0.202	0.105	0.107	0.115	0.123
U = 0.1734	0.235	0.250	0.295	0.343	0.176	0.183	0.203	0.228
Seattle								
U = 0.0245	0.136	0.138	0.144	0.150	0.075	0.076	0.078	0.081
U = 0.0726	0.185	0.192	0.212	0.234	0.117	0.119	0.128	0.138
U = 0.1734	0.271	0.287	0.342	0.400	0.197	0.205	0.229	0.257
Boise								
U = 0.0245	0.150	0.152	0.160	0.169	0.096	0.097	0.100	0.104
U = 0.0726	0.198	0.206	0.229	0.256	0.141	0.145	0.155	0.168
U = 0.1734	0.280	0.297	0.357	0.428	0.222	0.230	0.258	0.293
Vancouver								
U = 0.0245	0.145	0.148	0.154	0.162	0.082	0.082	0.085	0.088
U = 0.0726	0.198	0.205	0.226	0.252	0.128	0.131	0.141	0.152
U = 0.1734	0.293	0.310	0.368	0.426	0.215	0.223	0.248	0.280
Minneapolis								
U = 0.0245	0.302	0.304	0.310	0.317	0.185	0.186	0.190	0.194
U = 0.0726	0.391	0.398	0.417	0.434	0.259	0.262	0.274	0.287
U = 0.1734	0.550	0.567	0.618	0.655	0.388	0.397	0.425	0.455
Halifax								
U = 0.0245	0.263	0.265	0.273	0.282	0.152	0.154	0.159	0.164
U = 0.0726	0.340	0.349	0.377	0.404	0.222	0.226	0.242	0.259
U = 0.1734	0.476	0.498	0.568	0.634	0.345	0.357	0.394	0.435
Bismarck								
U = 0.0245	0.333	0.335	0.343	0.350	0.213	0.214	0.218	0.222
U = 0.0726	0.431	0.439	0.462	0.484	0.296	0.300	0.313	0.325
U = 0.1734	0.614	0.633	0.694	0.739	0.444	0.453	0.482	0.512
Anchorage								
U = 0.0245	0.385	0.388	0.396	0.405	0.239	0.240	0.245	0.250
U = 0.0726	0.506	0.514	0.538	0.559	0.340	0.344	0.358	0.372
U = 0.1734	0.730	0.750	0.803	0.854	0.515	0.524	0.554	0.584
Edmonton								
U = 0.0245	0.389	0.392	0.401	0.412	0.258	0.260	0.265	0.270
U = 0.0726	0.506	0.515	0.543	0.568	0.358	0.362	0.377	0.394
U = 0.1734	0.720	0.742	0.813	0.870	0.529	0.540	0.574	0.610

TABLE 4
Regression Statistics from DOE-2 Simulations of Annual HVAC Electricity and Gas Use for Residential and Nonresidential Buildings (Electricity in kWh/ft², and Gas in therm/ft²)

		Residential Building					Nonresidential Building				
Location	Fuel	R^2	C_0	C_1	C_2	C_3	R^2	C_0	C_1	C_2	C_3
Honolulu	Elec	1.00	5.091	–0.353	–7.328	37.579	1.00	5.210	0.030	–2.617	21.384
	Gas	0.96	–0.000	0.000	0.004	–0.003	0.94	–0.000	0.000	0.010	–0.007
Miami	Elec	1.00	5.154	–0.318	–5.334	39.364	1.00	5.169	0.047	–1.723	23.238
	Gas	0.99	–0.001	0.001	0.082	–0.065	1.00	0.000	0.001	0.074	–0.030
Tampa	Elec	1.00	4.219	–0.179	–3.558	32.583	1.00	4.500	0.083	–1.152	20.056
	Gas	0.99	0.000	0.004	0.270	–0.200	1.00	0.003	0.001	0.222	–0.085
Phoenix	Elec	1.00	4.948	–0.355	1.671	44.914	1.00	4.774	0.078	1.276	29.219
	Gas	0.99	–0.000	0.004	0.502	–0.401	1.00	0.009	0.001	0.398	–0.156
Lake Charles	Elec	1.00	4.115	–0.248	–3.361	36.687	1.00	4.211	0.018	–1.379	22.002
	Gas	1.00	0.017	0.004	0.595	–0.460	1.00	0.012	0.003	0.396	–0.162
San Diego	Elec	1.00	2.644	–0.227	–6.598	30.033	1.00	2.904	0.095	–3.837	18.416
	Gas	0.97	–0.009	0.011	0.428	–0.400	1.00	0.001	0.002	0.348	–0.143
Fort Worth	Elec	1.00	4.136	–0.259	–0.339	32.299	1.00	3.998	0.049	0.416	19.207
	Gas	1.00	0.036	0.006	0.864	–0.611	1.00	0.024	0.003	0.568	–0.225
San Bernardino	Elec	1.00	3.232	–0.152	–3.308	35.228	1.00	3.481	0.099	–2.329	23.352
	Gas	0.99	0.002	0.008	0.868	–0.693	1.00	0.014	0.003	0.690	–0.280
Atlanta	Elec	1.00	3.166	–0.182	–4.422	31.908	1.00	3.304	0.065	–2.547	19.618
	Gas	1.00	0.054	0.006	1.150	–0.754	1.00	0.032	0.003	0.790	–0.319
San Francisco	Elec	1.00	1.731	–0.224	–2.627	22.224	1.00	1.906	0.035	–2.107	12.790
	Gas	0.99	0.011	0.015	1.367	–1.210	1.00	0.018	0.003	0.803	–0.329
Amarillo	Elec	1.00	3.202	–0.273	–2.764	32.751	1.00	3.127	–0.003	–1.581	19.015
	Gas	1.00	0.083	0.008	1.570	–0.998	1.00	0.055	0.004	1.056	–0.406
Portland	Elec	1.00	2.066	–0.065	–1.211	18.128	1.00	2.104	0.048	–1.152	12.541
	Gas	1.00	0.095	0.005	1.650	–0.909	1.00	0.045	0.005	1.154	–0.450
Seattle	Elec	1.00	1.872	–0.142	–2.377	18.024	1.00	1.829	0.035	–1.591	11.824
	Gas	1.00	0.109	0.008	1.942	–1.107	1.00	0.050	0.006	1.307	–0.520
Boise	Elec	1.00	2.688	–0.162	–1.060	27.320	1.00	2.644	0.046	–0.640	17.271
	Gas	1.00	0.127	0.005	2.028	–1.246	1.00	0.073	0.005	1.404	–0.608
Vancouver	Elec	0.99	1.722	–0.010	–2.795	16.816	1.00	1.743	0.035	–2.884	12.125
	Gas	1.00	0.119	0.005	2.052	–1.133	1.00	0.057	0.005	1.413	–0.557
Minneapolis	Elec	0.99	2.342	–0.038	3.306	15.862	1.00	2.464	0.040	–1.107	13.382
	Gas	1.00	0.264	0.001	2.502	–0.880	1.00	0.155	–0.000	1.871	–0.546
Halifax	Elec	0.99	1.823	–0.131	–1.305	19.955	1.00	1.875	0.009	–2.197	13.594
	Gas	1.00	0.226	0.006	2.696	–1.343	1.00	0.122	0.002	1.994	–0.751
Bismarck	Elec	0.99	2.403	–0.020	1.131	20.015	1.00	2.375	0.038	–1.123	14.146
	Gas	1.00	0.289	0.000	2.880	–1.038	1.00	0.179	0.000	2.068	–0.560
Anchorage	Elec	0.99	1.537	0.125	3.604	7.374	1.00	1.428	0.067	–1.244	8.638
	Gas	1.00	0.337	–0.005	3.253	–0.988	1.00	0.203	–0.004	2.355	–0.546
Edmonton	Elec	0.99	1.898	0.040	2.855	13.905	1.00	1.770	0.074	–1.050	11.371
	Gas	1.00	0.340	–0.001	3.392	–1.234	1.00	0.222	–0.003	2.423	–0.654

TABLE 5
Estimated Roof Composite U-Factor [U2/U1] with Zero Net Energy Cost for Residential and Nonresidential Buildings; Roof Absorptivity (Initial = 0.80, Final = 0.45)

U2/U1: Based on Energy Cost of 0.66 $/Therm and 0.08 $/kWh						
Location	Residential Building			Nonresidential Building		
	U1 = 0.1734 R = 3	U1 = 0.0726 R = 11	U1 = 0.0245 R = 38	U1 = 0.1734 R = 3	U1 = 0.0726 R = 11	U1 = 0.0245 R = 38
Honolulu	2.295	2.192	1.845	2.066	2.079	2.122
Miami	2.012	1.945	1.719	1.883	1.899	1.953
Tampa	1.836	1.803	1.691	1.741	1.769	1.863
Phoenix	1.567	1.530	1.407	1.581	1.596	1.646
Lake Charles	1.677	1.641	1.516	1.654	1.664	1.697
San Diego	2.013	1.970	1.824	1.921	1.966	2.117
Fort Worth	1.479	1.448	1.345	1.482	1.497	1.550
San Bernardino	1.593	1.578	1.530	1.593	1.620	1.711
Atlanta	1.524	1.502	1.425	1.528	1.550	1.625
San Francisco	1.288	1.268	1.201	1.402	1.420	1.481
Amarillo	1.385	1.357	1.264	1.391	1.397	1.418
Portland	1.214	1.210	1.197	1.265	1.285	1.353
Seattle	1.168	1.155	1.114	1.223	1.241	1.304
Boise	1.245	1.231	1.183	1.271	1.286	1.337
Vancouver	1.153	1.158	1.174	1.229	1.247	1.306
Minneapolis	1.106	1.103	1.092	1.174	1.179	1.199
Halifax	1.118	1.109	1.079	1.150	1.154	1.167
Bismarck	1.132	1.130	1.125	1.169	1.174	1.192
Anchorage	0.997	1.005	1.032	1.076	1.080	1.096
Edmonton	1.042	1.045	1.054	1.101	1.108	1.130

TABLE 6
Estimated Revised Roof R-Value for Zero Net Energy Cost for Residential and Nonresidential Buildings; Roof Absorptivity (A1=0.80, A2=0.45)

Revised R-Value: Based on Energy Cost of 0.66 $/Therm and 0.08 $/kWh						
Location	Residential Building			Nonresidential Building		
	U1 = 0.1734 R = 3	U1 = 0.0726 R = 11	U1 = 0.0245 R = 38	U1 = 0.1734 R = 3	U1 = 0.0726 R = 11	U1 = 0.0245 R = 38
Honolulu	-0.3	3.5	19.4	0.0	3.9	16.5
Miami	0.1	4.3	21.0	0.3	4.5	18.2
Tampa	0.4	4.9	21.4	0.5	5.0	19.2
Phoenix	0.9	6.2	26.2	0.9	5.9	22.0
Lake Charles	0.7	5.6	24.2	0.7	5.5	21.3
San Diego	0.1	4.2	19.6	0.2	4.2	16.5
Fort Worth	1.1	6.7	27.5	1.1	6.4	23.5
San Bernardino	0.9	6.0	23.9	0.9	5.7	21.1
Atlanta	1.0	6.4	25.9	1.0	6.1	22.4
San Francisco	1.7	8.1	31.2	1.3	6.9	24.8
Amarillo	1.4	7.4	29.5	1.4	7.1	26.1
Portland	2.0	8.6	31.4	1.8	8.0	27.4
Seattle	2.2	9.2	33.9	1.9	8.3	28.6
Boise	1.9	8.4	31.7	1.8	7.9	27.7
Vancouver	2.2	9.1	32.0	1.9	8.3	28.5
Minneapolis	2.4	9.7	34.5	2.1	8.9	31.2
Halifax	2.4	9.7	35.1	2.2	9.2	32.2
Bismarck	2.3	9.4	33.5	2.2	9.0	31.5
Anchorage	3.0	10.9	36.8	2.6	10.0	34.4
Edmonton	2.8	10.4	36.0	2.5	9.7	33.3

U-factors resulting from these calculations are shown in Table 5. Also calculated were the revised R-value of the roof from U_2, shown in Table 6. Note that in Table 5, the U-factor for almost all of the climates is greater than 1, and in Table 6, there is a net reduction in roof R-value, indicating that even in cold climates such as Anchorage there is a net benefit to having a reflective roof. This point was fairly counter intuitive, so we investigated this observation further. In our calculations, DOE-2 sized the HVAC equipment. It turns out that in almost all the climates, DOE-2 had sized the systems based on summer cooling load. Since reflective roofs result in lower summertime cooling loads, accordingly, smaller systems are sized. A smaller system will also use less electricity during wintertime. Most energy savings in cold climates were due to smaller fans. In order to analyze the impact of the size of the fans, we performed limited simulations by keeping the fan size constant for both absorptive and reflective roofs. Then the energy savings for cold climates (climate Bins 15 and 18 to 23) turned into penalties. Therefore, for the remainder of this study, we assumed that buildings in cold climates should not be candidates for reflective roof applications. We assigned a U-factor of 1 for these cold climates. Note that in warm climates, buildings with reflective roofs will indeed require a smaller HVAC system compared to buildings with dark roofs. A smaller system has a lower initial cost and, hence, offers additional savings. To simplify the table of calculated U-factors, we suggest using the U-factor for medium roof R-value (R11) for each building type as a single value representing the adjustment in roof U-factor for each climate (Table 7).

OPTIMIZATION OF ROOF REFLECTANCE AND INSULATION

The above calculations for the trade-off between roof insulation and roof absorptance is carried out based on the assumption that the net energy cost should stay constant. However, we can also calculate the trade-off if the net energy cost is optimized. Figure 2 illustrates this point. Ignoring the installation cost, the cost of insulation is directly proportional to the thickness of insulation (typically $1/m^2 per unit of R-value). It is then assumed that the annualized cost of insulation is inversely proportional to the roof U-factor, i.e.,

$$\text{Cost}_{\text{insulation}} = D/U. \tag{3}$$

The total (T) annualized energy and insulation cost is then

$$T = D/U + C_0 + C_1 a + (C_2 + C_3 a)U. \tag{4}$$

The optimum solution for U such that the annualized cost is minimized can be obtained from

$$U_{opt} = D^{1/2}(C_3 a + C_2)^{-1/2} \tag{5}$$

After a few simple algebraic manipulations, ignoring the term $C_1\ a$, and assuming that the U-factor of insulation is always optimized (i.e., $U_1 = U_{opt1}$), it can be shown that

$$\frac{U_{opt2}}{U_{opt1}} = \left(\frac{U_2}{U_{opt1}}\right)^{1/2}. \tag{6}$$

Hence, take the square route of the U-factors developed in Table 7 (under "Constant Energy Use") and calculate the optimum U-factor such that the annualized cost of the roof insulation and energy is minimized. The results are also shown in Table 7 under "Optimum."

TABLE 7
Recommended Roof Composite U-Factor [U2/U1] Adjustment for Residential and Nonresidential Buildings

Location	Bin	Constant Energy Use		Optimum	
		Resid.	Nonres.	Resid.	Nonres.
Honolulu	2	2.20	2.08	1.48	1.44
Miami	2	1.95	1.90	1.40	1.38
Tampa	3	1.80	1.77	1.34	1.33
Phoenix	5	1.53	1.60	1.24	1.26
Lake Charles	6	1.64	1.66	1.28	1.29
San Diego	7	1.97	1.97	1.40	1.40
Fort Worth	8	1.45	1.50	1.20	1.22
San Bernardino	9	1.58	1.62	1.26	1.27
Atlanta	11	1.50	1.55	1.22	1.25
San Francisco	12	1.27	1.42	1.13	1.19
Amarillo	13	1.36	1.40	1.17	1.18
Portland	14	1.21	1.29	1.10	1.14
Seattle	15	1.00	1.00	1.00	1.00
Boise	17	1.23	1.29	1.11	1.14
Vancouver	18	1.00	1.00	1.00	1.00
Minneapolis	19	1.00	1.00	1.00	1.00
Halifax	20	1.00	1.00	1.00	1.00
Bismarck	21	1.00	1.00	1.00	1.00
Anchorage	22	1.00	1.00	1.00	1.00
Edmonton	23	1.00	1.00	1.00	1.00

Note: (U-factors for two cases are shown: Constant energy cost case and optimum annualized energy and roof insulation cost. base roof absorptivity is 0.80; U-factors are calculated for roofs with 0.45 absorptance. Energy cost are calculated using rates of 0.66 $/therm and 0.08 $/kwh).

FINAL U-FACTORS USED IN ASHRAE STANDARD

The ASHRAE 90.1 Envelope Subcommittee used the results for R-11 insulation from Table 5 to develop a U-factor multiplier for high-albedo roofs for ASHRAE 90.1-1989R. The subcommittee chose to use a base-case albedo (reflectivity) of 0.30 for roofs because this was the basis for the insulation optimizations in ASHRAE 90.1-1989R. Assuming the results in Table 5 are linear for incremental changes in base-

TABLE 8

Basis For U-Factor Multipliers for High-Albedo Roofs in ASHRAE 90.1-1989R, June 1997 Draft (Base Roof Absorptivity is 0.70. High-albedo Absorptivity is 0.45)

		Constant Energy		Optimum			Multiplier	
Location	HDD65	Res.	Nonres.	Res.	Nonres.	HDD Range in 90.1	Recommended	For 90.1
Honolulu	0	1.86	1.77	1.36	1.33	0-900	1.3	0.77
Miami	227	1.68	1.64	1.30	1.28	0-900	1.3	0.77
Tampa	604	1.57	1.55	1.25	1.24	0-900	1.3	0.77
Phoenix	1356	1.38	1.43	1.17	1.20	901-1800	1.2	0.83
Lake Charles	1535	1.46	1.47	1.21	1.21	901-1800	1.2	0.83
San Diego	1076	1.69	1.69	1.30	1.30	901-1800	1.2	0.83
Fort Worth	2376	1.32	1.36	1.15	1.16	1801-2700	1.17	0.85
San Bernardino	2103	1.41	1.44	1.19	1.20	1801-2700	1.17	0.85
Atlanta	3022	1.36	1.39	1.16	1.18	2701-3600	1.16	0.86
San Francisco	3238	1.19	1.30	1.09	1.14	2701-3600	1.16	0.86
Amarillo	4226	1.26	1.29	1.12	1.13	3601-4500	1.0	1.00
Portland	4626	1.15	1.21	1.07	1.10	4501-5400	1.0	1.00
Boise	5918	1.16	1.21	1.08	1.10.	5401-6300	1.0	1.00

case and high-albedo reflectivities, the values are multiplied by 5/7, which is the difference between the high-albedo roof (reflectivity of 0.55) and the base roof used in insulation optimizations (0.30), i.e., a Δ Albedo = 0.25, divided by the difference between the high-albedo roof and a base case of 0.20, i.e., a Δ Albedo = 0.35, used in our analysis. These values are listed under "Constant Energy" in Table 8. The square roots of these values are listed under "Optimum" in Table 8. The "Optimum" values were grouped according to 900 HDD intervals consistent with ASHRAE 90.1-1989R. Within these grouping, "recommended" values are approximate averages within 900 HDD groupings. One set of multipliers is used for both building types.

The actual language in the June 1997 draft for ASHRAE 90.1-1989R uses a U-factor multiplier to be applied to the proposed roof U-factor. This adjusted U-factor is used to comply with the standard. The multipliers are the inverse of the "recommended" values in Table 8. The multipliers can be used for exterior roofs other than ventilated attics. They cannot be used for roofs of semi-heated spaces. To use the multipliers, the high-albedo roof surface must have a total solar reflectance of at least 0.70 when tested in accordance with ASTM-E 903 and a thermal emittance of at least 0.8 when tested in accordance with ASTM-E 408. There are no multipliers for climates with greater than 3600 HDD.

CONCLUSION

In this study, the results of an analysis to account for energy-saving benefits of reflective roofs have been documented. The results are shown as factors that reduce the amount of insulation required for buildings with reflective roofs.

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