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Part-Load Performance Characterization and Energy Savings Potential of the RTU Challenge Unit: Carrier WeatherExpert

W Wang
S Katipamula
DJ Taasevigen

September 2015

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ABSTRACT

In 2011, the U.S. Department of Energy's Building Technology Office (DOE's BTO), with help from the Better Buildings Alliance (BBA) members, developed a specification (RTU Challenge) for high performance rooftop air-conditioning units with capacity ranges between 10 and 20 tons (DOE 2013). In April 2013, Carrier's 10-ton WeatherExpert unit model was recognized by DOE to have met the RTU Challenge specifications. Carrier also committed to have its entire line of WeatherExpert models for commercial buildings compliant with integrated energy efficiency ratio (IEER) meeting the RTU Challenge requirement. This report documents the development of part-load performance curves and their use with the EnergyPlus simulation tool to estimate the potential savings from the use of WeatherExpert units compared to other standard options.

A detailed EnergyPlus model was developed for a prototypical big-box retail store. The model used the performance curves from the new model along with detailed energy management control code to estimate the energy consumption of the prototypical big-box retail store in three locations. The energy consumption by the big-box store was then compared to a store that used three different reference units. The first reference unit (Reference 1) represents existing rooftop units (RTUs) in the field, so it can be considered the baseline to estimate potential energy savings from other RTU replacement options. The second reference unit (Reference 2) represents RTUs in the market that just meet the current (2015) Federal regulations for commercial equipment standards, so it can be used as the baseline to estimate the potential for energy savings from WeatherExpert units in comparison with new RTUs that meet the minimum efficiency requirements. The third reference unit (Reference 3) represents units that meet ASHRAE 90.1-2010 requirements. For RTUs with cooling capacity greater than 11,000 Btu/h, ASHRAE 90.1-2010 (ASHRAE 2010) requires two-speed fan control or variable-speed fan control.

The following conclusion can be drawn about the comparison of energy cost for WeatherExpert unit compared to the three reference units:

- Using Reference 1 as the baseline, WeatherExpert units result in about 45% lower heating, ventilation and air conditioning (HVAC) energy cost in Houston, 55% lower cost in Los Angeles, and 35% lower cost in Chicago. The percentage savings of electricity cost is more than 50% for all three locations.
- Using Reference 2 as the baseline, WeatherExpert units result in about 39% lower HVAC energy cost in Houston, 52% lower cost in Los Angeles, and 32% lower cost in Chicago. The percentage savings of electricity cost is 44%, 55%, and 57%, respectively for the three locations.
- Using Reference 3 as the baseline, WeatherExpert units result in about 25% lower HVAC energy cost in Houston, 35% lower cost in Los Angeles, and 18% lower cost in Chicago. The percentage savings of electricity cost is 29%, 38%, and 37%, respectively.

Based on the simulation results, the WeatherExpert RTU Challenge unit, if widely adopted, could lead to significant energy, cost and emission reductions. Because the cost of these units was not available and because the costs would be specific to a given installation, no attempt was made to estimate the potential payback periods associated with any of the three reference scenarios. However, if the incremental cost relative to any of the three reference cases is known, one can easily estimate a simple payback period.

ACKNOWLEDGEMENT

The authors would like to acknowledge the Buildings Technologies Office of the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy for supporting this research, development and demonstration effort. The authors would also like to thank Charles Llenza, Technology Development Manager at DOE, and Linda Sandahl, Program Manager at PNNL for their valuable guidance; Robert Lutes for providing the technical review of the document; and Sue Arey for editorial support. The authors would also like to thank Jim Deltoro and David Sabatino from Carrier Corporation for valuable discussions on WeatherExpert product data and curve development.

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1 INTRODUCTION

In 2011, the U.S. Department of Energy's Building Technology Office (DOE's BTO), with help from the Better Buildings Alliance (BBA) members, developed a specification for high performance rooftop air-conditioning units (also known as the RTU Challenge) with capacity ranges between 10 and 20 tons (DOE 2013). The goal of the RTU Challenge was to spur the market introduction of cost-effective, high-performance commercial rooftop unit air conditioners. Five manufacturers—Daikin, Carrier, Lennox, 7AC Technologies, and Rheem—originally showed interest in developing products that meet the RTU Challenge requirements. In April 2013, Carrier's 10-ton WeatherExpert units were recognized by DOE to meet the RTU Challenge specifications. Carrier also committed to have its entire line of WeatherExpert models for commercial buildings (ranging from 6- to 23-ton units) compliant with integrated energy efficiency ratio (IEER) meeting the RTU Challenge requirement.

With funding from the DOE's BTO, Pacific Northwest National Laboratory (PNNL) coordinated the laboratory testing and verified the manufacturer's RTU specifications. The part-load performance data provided by the manufacturer were used to develop the RTU's part-load performance curves. These curves were then used in EnergyPlus simulation programs to model the WeatherExpert unit's performance. This document reports 1) development of performance curves for WeatherExpert units; and 2) the simulated energy and cost savings for a prototypical "big-box" building at three locations (Houston, Los Angeles, and Chicago) using WeatherExpert units compared to the same building that uses conventional RTUs.

The development of the WeatherExpert performance curves are discussed in the Section 2, followed by the description of the prototypical building characteristics in Section 3. The energy management system used to model the WeatherExpert unit controls in EnergyPlus is discussed in Section 4. The simulation results are provided in Section 5. The report concludes with a discussion in Section 6 and list of references in Section 7.

2 PERFORMANCE CURVE DEVELOPMENT FOR WEATHEREXPERT

The performance data and the curves derived from those data are covered in this section.

2.1 PERFORMANCE DATA OVERVIEW

The data that was used to develop the performance curves were provided by Carrier Corporation. These data were developed using Carrier's proprietary computer software. PNNL validated the output of Carrier's software by comparing it to the data obtained from laboratory tests. The laboratory tests were conducted at Carrier's facility and witnessed by PNNL staff.

Before initiating the part-load tests, several reference tests were run to verify that the refrigerant charge was appropriate and to validate the unit performance at the Air-Conditioning, Heating and Refrigeration Institute (AHRI 2007) rated test conditions. The validated test unit was then used to generate part load performance tests that were used for software validation.

A series of steady-state tests were conducted to quantify the RTU performance at different conditions (indoor and outdoor temperatures): two outdoor dry-bulb temperatures (65°F and 110°F), one indoor dry-bulb temperature (80°F), and two indoor wet-bulb temperatures (61°F and 67°F). The indoor dry-bulb and wet-bulb temperatures refer to the air entering the cooling coil. All tests listed were conducted at the rated supply air flow rate for each direct expansion cooling stage (i.e., the 1st compressor alone is on, the 2nd compressor alone is on, both the 1st and the 2nd compressors are on).

The Carrier software was used to generate data from the same conditions and estimates from the software were compared to the laboratory test data. The air-side and refrigerant-side capacities generated by the software had less than 5% deviation when compared to the laboratory test data. The supply fan consumption reported by the software at certain speeds had significant deviation (>5%) when compared to the laboratory tests. Carrier noted that the difference in the supply fan consumption reported by the software was caused by the use of an incorrect fan performance model in the software. After correcting the fan performance maps, the supply fan consumption reported by the software compared well with the laboratory test data.

The validated Carrier software was used to generate the performance data for the WeatherExpert products with different sizes, as shown in Table 1. For each size, the performance data covers the full combinations of seven outdoor dry-bulb temperatures and seven indoor wet-bulb temperatures, as shown in Table 2.

Table 1: Carrier WeatherExpert models for which performance curves were developed

Model Number	Size (Tons)
48LCF007	6
48LCF008	7.5
48LCF009	8.5
48LCF012	10
48LCF014	12.5
48LCF017	15
48LCF020	17.5
48LCF024	20
48LCF026	23

Table 2: Test matrix used to develop part-load curves as a function of temperature and flow fraction

Test	Outdoor Dry-Bulb Temperature (ºF)	Indoor Wet-Bulb Temperature (ºF)
B1	65	54
B2	65	58
B3	65	62
B4	65	67
B5	65	72
B6	65	76
B7	65	80
B8	75	54
B9	75	58
B10	75	62
B11	75	67
B12	75	72
B13	75	76
B14	75	80
B15	85	54
B16	85	58
B17	85	62
B18	85	67
B19	85	72
B20	85	76
B21	85	80
B22	95	54
B23	95	58
B24	95	62
B25	95	67
B26	95	72

Test	Outdoor Dry-Bulb Temperature (ºF)	Indoor Wet-Bulb Temperature (ºF)
B27	95	76
B28	95	80
B29	105	54
B30	105	58
B31	105	62
B32	105	67
B33	105	72
B34	105	76
B35	105	80
B36	115	54
B37	115	58
B38	115	62
B39	115	67
B40	115	72
B41	115	76
B42	115	80
B43	125	54
B44	125	58
B45	125	62
B46	125	67
B47	125	72
B48	125	76
B49	125	80

2.2 Performance Characterization Approach

Because the WeatherExpert unit has three discrete cooling stages. Each stage has a constant supply air flow and the compressor cycles on and off to meet the space thermal loads. Thus, the equation forms of the various performance curves used to model packaged cooling equipment in EnergyPlus are appropriate to characterize the WeatherExpert unit's part-load performance.

In EnergyPlus, five performance curves are used:

- Total cooling capacity modifier curve as a function of temperature. As Equation 1 shows, this is a biquadratic curve with two independent variables: wet-bulb temperature of the air entering the cooling coil ($T_{wb,i}$), and dry-bulb temperature of the air entering the air-cooled condenser coil ($T_{c,i}$). The output of this curve indicates the ratio of the total maximum cooling capacity at the specific operating conditions ($T_{wb,i}$ and $T_{c,i}$) and the total maximum cooling capacity at rated conditions ($T_{wb,i} = 67$°F and $T_{c,i} = 95$°F).

$$TotCapTempModFac = C_0 + C_1\left(T_{wb,i}\right) + C_2\left(T_{wb,i}\right)^2 + C_3\left(T_{c,i}\right) + C_4\left(T_{c,i}\right)^2 + C_5(T_{wb,i})(T_{c,i}) \qquad (1)$$

- Energy input ratio (EIR) modifier curve as a function of temperature. EIR is the inverse of the coefficient of performance (COP). Similar to the capacity modifier curve as a function of temperature, this is a biquadratic curve (Equation 2) with two independent variables: $T_{wb,i}$ and $T_{c,i}$. The output of this curve indicates the ratio of the EIR at specific operating conditions ($T_{wb,i}$ and $T_{c,i}$) and the EIR at the rated conditions ($T_{wb,i} = 67°F$ and $T_{c,i} = 95°F$).

$$EIRTempModFac = C_0 + C_1\left(T_{wb,i}\right) + C_2\left(T_{wb,i}\right)^2 + C_3\left(T_{c,i}\right) + C_4\left(T_{c,i}\right)^2 + C_5(T_{wb,i})(T_{c,i}) \quad (2)$$

- Total cooling capacity modifier curve as a function of flow fraction. As Equation 3 shows, this is a quadratic (or cubic) curve with the independent variable being the air flow fraction (ff). The air flow fraction refers to the ratio of the actual air flow rate across the cooling coil to the rated air flow rate. The output of this curve indicates the ratio of the total cooling capacity at the specific air flow fraction and the total maximum cooling capacity at the rated air flow rate (ff = 1).

$$TotCapFlowModFac = C_0 + C_1(ff) + C_2(ff)^2 + C_3(ff)^3 \quad (3)$$

- Energy input ratio (EIR) modifier curve as a function of flow fraction. This is a quadratic (or cubic) curve (Equation 4) with the independent variable being the air flow fraction (ff). The output of this curve indicates the ratio of the EIR at the specific air flow fraction and the EIR at the rated air flow rate (ff = 1).

$$EIRFlowModFac = C_0 + C_1(ff) + C_2(ff)^2 + C_3(ff)^3 \quad (4)$$

- Part-load fraction (PLF) correlation as a function of part-load ratio (PLR). This is a quadratic (or cubic) curve (Equation 5) with the independent variable being part-load ratio. Dividing the EIR at specific temperature and air flow conditions by the output of this curve leads to the effective EIR after accounting for the efficiency loss of compressor cycling.

$$PLF = C_0 + C_1(PLR) + C_2(PLR)^2 + C_3(PLR)^3 \quad (5)$$

WeatherExpert units have three stages of cooling that approximately provide 40%, 60% and 100% capacities. The supply air flow is varied for each stage, but it is constant within each stage. Therefore, three sets of curves are needed to characterize the RTU performance at three stages.

For each curve, the regression coefficients are provided in a table for each size (WeatherExpert model) and stage of operation. A generic curve covering all nine product models is also provided for each of the three stages to facilitate future modeling needs when the RTU capacity is unknown. The generic curve coefficients are obtained using the average of the results of the nine models for each test condition of outdoor air dry-bulb and indoor air wet-bulb. Considering that different simulation programs may offer a choice of units, regression coefficients are provided in both International System of Units (SI) units and inch-pound (IP) units. An example scatter chart comparing the model-predicted values to the actuals is shown for stage 3 (100% capacity) for product 48LCF014 to demonstrate the curve fitting of each curve groups.

2.3 TOTAL COOLING CAPACITY MODIFIER CURVE AS A FUNCTION OF TEMPERATURE

Table 3 (IP units) and

Table 4 (SI units) show the regression coefficients and coefficient of determination (R^2), for Equation 1. The regression equations fit the experimental data very well, with R^2 close to 1 for all cases, except model 48LCF017 stage 1. This model has low R^2 because its test data have several outliers in gross capacity, causing the capacity modifiers to be off from those calculated by Equation 1. Figure 1 shows an example plot of the equation versus the test data for model 48LCF014 stage 3 (both compressors operating).

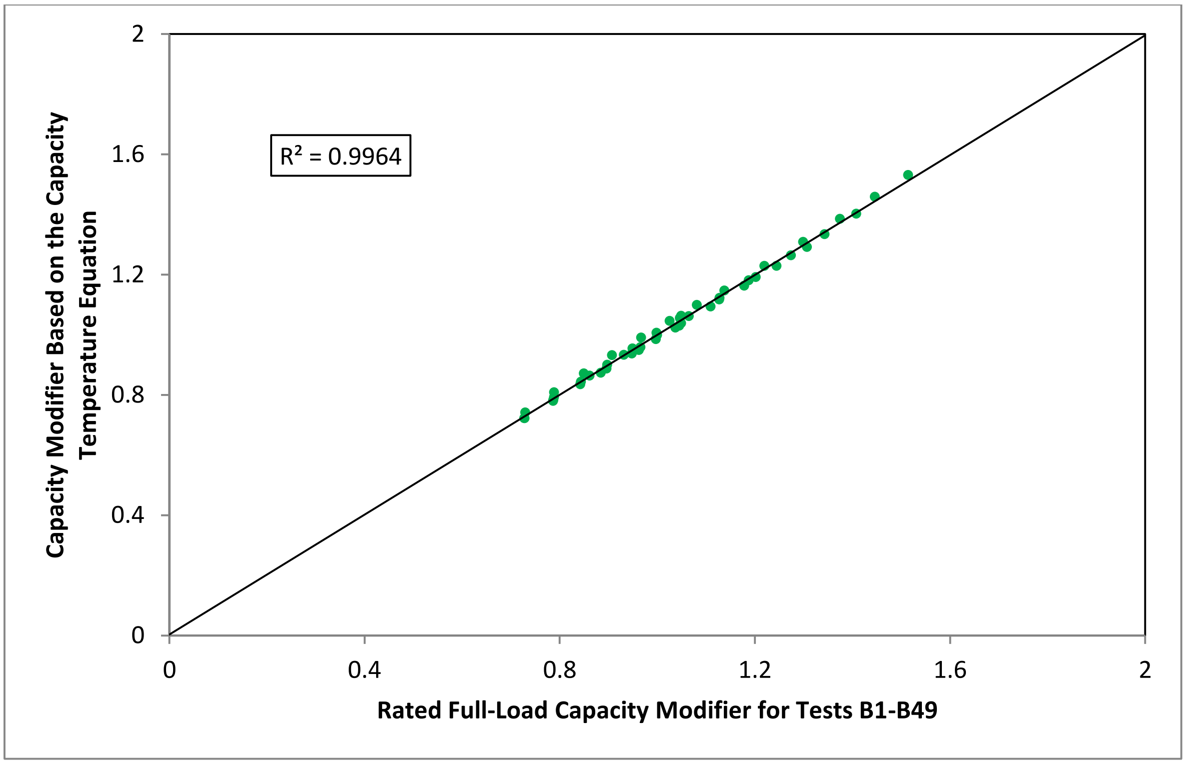

Figure 1: Comparison of predicted and measured capacity modifiers as a function of indoor wet-bulb and outdoor dry-bulb temperature for 48LCF014 high capacity

Table 3: Regression coefficients and coefficient of determination (based on IP units) for the total cooling capacity modifier curve as a function of indoor wet-bulb and outdoor dry-bulb temperature (Equation 1) for each model and stage of operation

Model & Stage	Coefficient						R^2
	C_0	C_1	C_2	C_3	C_4	C_5	
48LCF007 Stage 3	1.88770137	-0.03973986	0.00048300	0.00515797	-0.00001598	-0.00011610	0.995
48LCF008 Stage 3	2.15117157	-0.04716523	0.00058369	0.00428127	-0.00001496	-0.00013921	0.996
48LCF009 Stage 3	2.05801413	-0.04470405	0.00053409	0.00459700	-0.00001661	-0.00011763	0.995
48LCF012 Stage 3	2.42094015	-0.05568373	0.00061113	0.00434620	-0.00002255	-0.00010144	0.997
48LCF014 Stage 3	2.40299461	-0.05300267	0.00058900	0.00286253	-0.00001297	-0.00010249	0.996
48LCF017 Stage 3	2.19305140	-0.04756003	0.00055564	0.00337682	-0.00001195	-0.00011246	0.996
48LCF020 Stage 3	2.33572381	-0.04969075	0.00054911	0.00242174	-0.00001082	-0.00009502	0.996
48LCF024 Stage 3	2.11302381	-0.04682109	0.00052597	0.00431297	-0.00001771	-0.00009232	0.996
48LCF026 Stage 3	1.95910122	-0.04239036	0.00050923	0.00411157	-0.00001634	-0.00010232	0.996
Generic Stage 3	2.16908023	-0.04741753	0.00054899	0.00394090	-0.00001554	-0.00010878	0.996
48LCF007 Stage 2	1.88346058	-0.04070885	0.00046910	0.00589279	-0.00001599	-0.00010612	0.995
48LCF008 Stage 2	2.90593189	-0.06790882	0.00074288	0.00375015	-0.00001485	-0.00014328	0.997
48LCF009 Stage 2	2.34981387	-0.05410228	0.00059175	0.00461566	-0.00001552	-0.00010677	0.996
48LCF012 Stage 2	2.61989512	-0.06360188	0.00067644	0.00508221	-0.00002757	-0.00009916	0.996
48LCF014 Stage 2	3.78739019	-0.08775997	0.00089925	0.00143539	-0.00001528	-0.00014596	0.997
48LCF017 Stage 2	2.90266348	-0.06360058	0.00066527	0.00154985	0.00000292	-0.00012448	0.997
48LCF020 Stage 2	2.47976890	-0.05239725	0.00059874	0.00186646	0.00000421	-0.00013643	0.995
48LCF024 Stage 2	2.45107391	-0.05749301	0.00062198	0.00483019	-0.00002536	-0.00009783	0.996
48LCF026 Stage 2	2.25365961	-0.04970229	0.00056584	0.00403675	-0.00001463	-0.00011247	0.996
Generic Stage 2	2.62596194	-0.05969721	0.00064792	0.00367327	-0.00001356	-0.00011917	0.997
48LCF007 Stage 1	1.98664029	-0.04594168	0.00045708	0.00713854	-0.00001484	-0.00007772	0.994
48LCF008 Stage 1	3.44196054	-0.07911235	0.00080720	0.00299190	-0.00002070	-0.00013356	0.998
48LCF009 Stage 1	2.96057625	-0.06829051	0.00067184	0.00469120	-0.00002003	-0.00010198	0.997
48LCF012 Stage 1	3.05429848	-0.07139747	0.00068267	0.00461163	-0.00002159	-0.00008806	0.996
48LCF014 Stage 1	3.03288236	-0.07038643	0.00074492	0.00301506	-0.00001087	-0.00013237	0.996
48LCF017 Stage 1	1.71082659	-0.06236763	0.00077194	0.02781904	-0.00005194	-0.00033074	0.245
48LCF020 Stage 1	2.28684530	-0.05284604	0.00056637	0.00489275	-0.00001953	-0.00009049	0.995
48LCF024 Stage 1	3.52012967	-0.08132342	0.00087461	0.00016577	-0.00000583	-0.00015076	0.997
48LCF026 Stage 1	2.20446088	-0.05066083	0.00053853	0.00559091	-0.00001387	-0.00009870	0.995
Generic Stage 1	2.68873560	-0.06470293	0.00067946	0.00676853	-0.00001991	-0.00013382	0.971

Table 4: Regression coefficients and coefficient of determination (based on SI units) for the total cooling capacity modifier curve as a function of indoor wet-bulb and outdoor dry-bulb temperature (Equation 1) for each model and stage of operation

Model & Stage	**Coefficient**						**R^2**
	C_0	C_1	C_2	C_3	C_4	C_5	
48LCF007 Stage 3	1.05626136	-0.01231315	0.00128101	0.00050045	-0.00005015	-0.00036354	0.987
48LCF008 Stage 3	1.11361320	-0.01303585	0.001541906	-0.00226616	-4.6919E-05	-0.00043664	0.988
48LCF009 Stage 3	1.088541174	-0.01422508	0.001414658	-0.00063291	-5.2118E-05	-0.00036953	0.987
48LCF012 Stage 3	1.173433662	-0.02329992	0.001642333	-0.00086242	-7.0752E-05	-0.00031697	0.990
48LCF014 Stage 3	1.181694737	-0.02138802	0.001578309	-0.00243038	-4.0697E-05	-0.00032031	0.989
48LCF017 Stage 3	1.122289733	-0.01630214	0.001476913	-0.00196645	-3.7464E-05	-0.0003524	0.988
48LCF020 Stage 3	1.181904829	-0.02041008	0.00147186	-0.00252346	-0.00003394	-0.00029713	0.989
48LCF024 Stage 3	1.087629149	-0.01804774	0.00140494	0.00018459	-0.00005556	-0.00028902	0.989
48LCF026 Stage 3	1.041848152	-0.01238309	0.00134395	-0.00058415	-0.00005123	-0.00032092	0.989
Generic Stage 3	1.116357331	-0.01682279	0.00146176	-0.00117566	-0.00004876	-0.00034072	0.988
48LCF007 Stage 2	1.04799582	-0.01592144	0.00125955	0.00236548	-0.00005021	-0.00033134	0.986
48LCF008 Stage 2	1.330276861	-0.03055223	0.002012283	-0.00349151	-4.6615E-05	-0.00044607	0.990
48LCF009 Stage 2	1.149036743	-0.02362134	0.001596065	0.000122854	-4.8729E-05	-0.00033353	0.987
48LCF012 Stage 2	1.197266092	-0.02875237	0.001823387	-2.9116E-05	-8.6522E-05	-0.00030895	0.988
48LCF014 Stage 2	1.632642319	-0.04581590	0.00245274	-0.00781400	-0.00004796	-0.00045379	0.992
48LCF017 Stage 2	1.36803723	-0.03275007	0.001820489	-0.00422238	9.1464E-06	-0.00038694	0.990
48LCF020 Stage 2	1.239199546	-0.02126358	0.00161040	-0.00417818	0.00001320	-0.00042585	0.987
48LCF024 Stage 2	1.171578642	-0.02487359	0.00167148	-0.00013379	-0.00007957	-0.00030516	0.988
48LCF026 Stage 2	1.145927577	-0.01927066	0.00151749	-0.00113423	-0.00004587	-0.00035130	0.989
Generic Stage 2	1.25355120	-0.02698013	0.00175154	-0.00205721	-0.00004257	-0.00037144	0.989
48LCF007 Stage 1	1.05218133	-0.02644152	0.00126355	0.00635819	-0.00004656	-0.00024227	0.986
48LCF008 Stage 1	1.545727159	-0.04221447	0.002210618	-0.00497145	-6.4972E-05	-0.00041473	0.993
48LCF009 Stage 1	1.383346874	-0.03922157	0.001849693	-8.2786E-06	-6.2894E-05	-0.00031758	0.992
48LCF012 Stage 1	1.398923279	-0.04279979	0.001887273	0.000465037	-6.7772E-05	-0.00027331	0.992
48LCF014 Stage 1	1.371254283	-0.03420733	0.00202241	-0.00370460	-0.00003409	-0.00041155	0.989
48LCF017 Stage 1	1.008312017	-0.04058125	0.00245592	0.02395172	-0.00014828	-0.00108472	0.247
48LCF020 Stage 1	1.124609496	-0.02366986	0.00152404	0.00109999	-0.00006132	-0.00028270	0.986
48LCF024 Stage 1	1.511086842	-0.03728318	0.00236756	-0.00922805	-0.00001833	-0.00046927	0.991
48LCF026 Stage 1	1.112794818	-0.02447223	0.00146171	0.00249893	-0.00004350	-0.00030751	0.985
Generic Stage 1	1.27869290	-0.03454347	0.00189364	0.00182905	-0.00006086	-0.00042263	0.963

2.4 ENERGY INPUT RATIO (EIR) MODIFIER CURVE AS A FUNCTION OF TEMPERATURE

Table 5 (IP units) and Table 6 (SI units) show the regression coefficients and coefficient of determination of Equation 2 for nine Carrier models, each with three operating stages. The regression equation fit the experimental data very well, with R^2 close to 1 for each case. Figure 2 shows an example plot of the equation versus the test data for model 48LCF014 stage 3 (both compressors operating).

Table 5: Regression coefficients and coefficient of determination (based on IP units) for the EIR modifier curve as a function of indoor wet-bulb and outdoor dry-bulb temperature for each model and stage of operation

Model & Stage	Coefficient						R^2
	C_0	C_1	C_2	C_3	C_4	C_5	
48LCF007 Stage 3	-0.78712682	0.04818821	-0.00032456	-0.00552991	0.00018598	-0.00017793	0.997
48LCF008 Stage 3	-1.26672985	0.06464243	-0.00038068	-0.00627703	0.00025477	-0.00032155	0.994
48LCF009 Stage 3	-0.84839559	0.05043949	-0.00031567	-0.00588240	0.00021119	-0.00022848	0.995
48LCF012 Stage 3	-1.48097362	0.06927286	-0.00043722	-0.00336745	0.00020994	-0.00027679	0.994
48LCF014 Stage 3	-1.22910570	0.05776384	-0.00034724	-0.00323712	0.00020544	-0.00025461	0.996
48LCF017 Stage 3	-0.93466641	0.05202502	-0.00033541	-0.00344622	0.00018653	-0.00021900	0.995
48LCF020 Stage 3	-0.93864450	0.05042010	-0.00032476	-0.00325262	0.00017283	-0.00019274	0.997
48LCF024 Stage 3	-0.85574325	0.04751840	-0.00031338	-0.00192490	0.00015680	-0.00018035	0.996
48LCF026 Stage 3	-0.76259739	0.04479618	-0.00027038	-0.00212628	0.00017682	-0.00022163	0.996
Generic Stage 3	-1.01155368	0.05389628	-0.00033881	-0.00389377	0.00019559	-0.00023034	0.996
48LCF007 Stage 2	-0.80430575	0.04829014	-0.00035452	-0.00459799	0.00015391	-0.00012412	0.997
48LCF008 Stage 2	-2.06211437	0.09086013	-0.00056341	-0.00830035	0.00027748	-0.00034629	0.993
48LCF009 Stage 2	-1.18140267	0.05778590	-0.00038587	-0.00350707	0.00018243	-0.00019890	0.996
48LCF012 Stage 2	-1.81049814	0.07845024	-0.00050088	-0.00124626	0.00020488	-0.00030117	0.993
48LCF014 Stage 2	-2.29278597	0.10395297	-0.00060737	-0.01581079	0.00034719	-0.00040545	0.991
48LCF017 Stage 2	-1.32917928	0.06320815	-0.00045040	-0.00444776	0.00015882	-0.00014139	0.997
48LCF020 Stage 2	-1.02243161	0.05455685	-0.00038177	-0.00441758	0.00016832	-0.00016002	0.996
48LCF024 Stage 2	-1.45580750	0.06350866	-0.00040311	-0.00107193	0.00018832	-0.00024804	0.995
48LCF026 Stage 2	-0.93669201	0.05226218	-0.00033534	-0.00408095	0.00017857	-0.00020066	0.996
Generic Stage 2	-1.43280192	0.06809725	-0.00044252	-0.00527563	0.00020666	-0.00023623	0.995
48LCF007 Stage 1	-0.76968073	0.04201149	-0.00034390	-0.00148267	0.00008752	-0.00002497	0.999
48LCF008 Stage 1	-2.48193145	0.10642058	-0.00066801	-0.01343003	0.00031090	-0.00034310	0.992
48LCF009 Stage 1	-1.78938919	0.07858152	-0.00055320	-0.00724530	0.00018894	-0.00016072	0.996
48LCF012 Stage 1	-1.80000612	0.08084371	-0.00057774	-0.00773956	0.00018152	-0.00014767	0.996
48LCF014 Stage 1	-1.88743795	0.07808298	-0.00048862	-0.00549221	0.00024022	-0.00028242	0.995
48LCF017 Stage 1	-1.71331745	0.07894722	-0.00060541	-0.00530332	0.00014851	-0.00010979	0.940
48LCF020 Stage 1	-0.88456850	0.05068113	-0.00034001	-0.00360096	0.00016061	-0.00017096	0.996
48LCF024 Stage 1	-2.76880631	0.10653012	-0.00059780	-0.00394839	0.00031132	-0.00048852	0.989
48LCF026 Stage 1	-0.76560613	0.04512992	-0.00032368	-0.00285728	0.00012862	-0.00010938	0.998
Generic Stage 1	-1.65119376	0.07413652	-0.00049982	-0.00567775	0.00019535	-0.00020417	0.995

Table 6: Regression coefficients and coefficient of determination (based on SI units) for the EIR modifier curve as a function of indoor wet-bulb and outdoor dry-bulb temperature for each model and stage of operation

Model & Stage	**Coefficient**						**R^2**
	C_0	C_1	C_2	C_3	C_4	C_5	
48LCF007 Stage 3	0.33586765	0.02996111	-0.00082598	0.00152592	0.00058361	-0.00055483	0.994
48LCF008 Stage 3	0.25293455	0.04183108	-0.00094335	-0.00022579	0.00079961	-0.00099989	0.991
48LCF009 Stage 3	0.32627641	0.03134747	-0.00078279	0.00083520	0.00066275	-0.00070980	0.993
48LCF012 Stage 3	0.21962389	0.04656096	-0.00112993	0.00238109	0.00065887	-0.00086396	0.992
48LCF014 Stage 3	0.20109337	0.03944972	-0.00088872	0.00337634	0.00064467	-0.00079409	0.994
48LCF017 Stage 3	0.33401432	0.03242993	-0.00084414	0.00284524	0.00058536	-0.00068130	0.993
48LCF020 Stage 3	0.29857614	0.03344741	-0.00083794	0.00316168	0.00054233	-0.00060126	0.994
48LCF024 Stage 3	0.33742980	0.03044755	-0.00080470	0.00436961	0.00049204	-0.00056281	0.994
48LCF026 Stage 3	0.35909421	0.02816990	-0.00067041	0.00392043	0.00055486	-0.00069068	0.994
Generic Stage 3	0.29610115	0.03484946	-0.00085866	0.00246552	0.00061379	-0.00071762	0.993
48LCF007 Stage 2	0.33997244	0.03013060	-0.00092619	0.00261668	0.00048295	-0.00038889	0.995
48LCF008 Stage 2	0.06322447	0.06410659	-0.00147164	-0.00249789	0.00087114	-0.00108354	0.990
48LCF009 Stage 2	0.23538485	0.03803061	-0.00100173	0.00348694	0.00057259	-0.00062156	0.994
48LCF012 Stage 2	0.17026855	0.05286849	-0.00129874	0.00413239	0.00064312	-0.00094092	0.990
48LCF014 Stage 2	-0.01572676	0.07818653	-0.00159574	-0.01110306	0.00109021	-0.00126977	0.989
48LCF017 Stage 2	0.19807328	0.04374051	-0.00120752	0.00250233	0.00049841	-0.00044580	0.995
48LCF020 Stage 2	0.28764016	0.03523992	-0.00099307	0.00250583	0.00052825	-0.00050046	0.994
48LCF024 Stage 2	0.16885631	0.04276186	-0.00104266	0.00560315	0.00059111	-0.00077456	0.992
48LCF026 Stage 2	0.32054901	0.03491945	-0.00086788	0.00191869	0.00056037	-0.00062680	0.994
Generic Stage 2	0.19647137	0.04666495	-0.00115613	0.00101834	0.00064868	-0.00073914	0.993
48LCF007 Stage 1	0.30163669	0.02782546	-0.00093899	0.00620753	0.00027457	-0.00008109	0.998
48LCF008 Stage 1	-0.08509945	0.07923254	-0.00178424	-0.00740054	0.00097619	-0.00107883	0.991
48LCF009 Stage 1	0.06150606	0.05668848	-0.00149744	-0.00003040	0.00059298	-0.00050806	0.995
48LCF012 Stage 1	0.08735340	0.05868902	-0.00157585	-0.00098937	0.00056965	-0.00046821	0.995
48LCF014 Stage 1	0.00785175	0.05533369	-0.00127531	0.00185674	0.00075412	-0.00088385	0.993
48LCF017 Stage 1	0.14818324	0.05661805	-0.00173439	0.00150455	0.00046230	-0.00032812	0.935
48LCF020 Stage 1	0.34383152	0.03333342	-0.00088274	0.00240196	0.00050398	-0.00053387	0.994
48LCF024 Stage 1	-0.12752938	0.07833728	-0.00155035	0.00079079	0.00097768	-0.00152574	0.986
48LCF026 Stage 1	0.34448387	0.03005398	-0.00085754	0.00362200	0.00040357	-0.00034372	0.996
Generic Stage 1	0.12024641	0.05290132	-0.00134409	0.00088481	0.00061278	-0.00063906	0.993

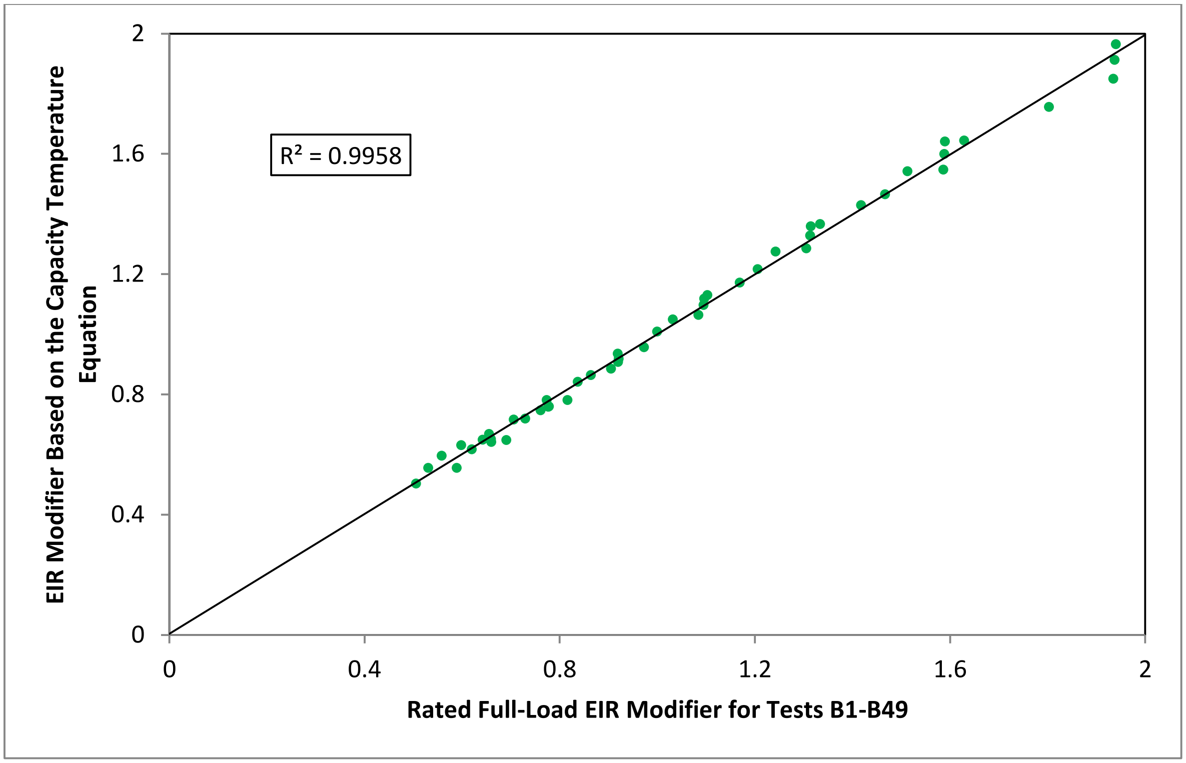

Figure 2: Comparison of predicted and measured EIR modifiers as a function of indoor wet-bulb and outdoor dry-bulb temperature for 48LCF014 high capacity

2.5 Cooling Capacity modifier curve as a function of flow fraction

Table 7 shows the regression coefficients and the coefficient of determination for the nine Carrier models using Equation 3. Because there are many different test temperature conditions corresponding to a given flow fraction, the capacity modifiers are averaged across those temperature conditions. The average results are used to obtain the regression coefficients. In addition, the curve coefficients in Table 7 do not distinguish between stages because the curves are very close for different stages. For all models, the regression equation fit the experimental data perfectly, with R^2 equal to 1 for each case. Figure 3 shows an example plot of the equation versus the test data for model 48LCF014 stage 3 (both compressors operating).

Table 7: Regression coefficients and coefficient of determination for the delivered cooling modifier curve as a function of flow fraction (Equation 3) for each model at the high stage of operation

Model & Stage	Coefficient				R^2
	C_0	C_1	C_2	C_3	
48LCF007	0.5448	0.8055	-0.4484	0.0983	1
48LCF008	0.3994	1.0646	-0.5964	0.1325	1
48LCF009	0.4722	0.9437	-0.5353	0.1196	1
48LCF012	0.4542	0.9587	-0.5285	0.1158	1
48LCF014	0.4736	0.9271	-0.5135	0.1129	1
48LCF017	0.4615	0.9502	-0.5273	0.1158	1
48LCF020	0.5165	0.8602	-0.484	0.1075	1
48LCF024	0.523	0.8463	-0.4746	0.1054	1
48LCF026	0.5017	0.8801	-0.4904	0.1087	1
Generic Curve	0.5076	0.8441	-0.4455	0.0933	1

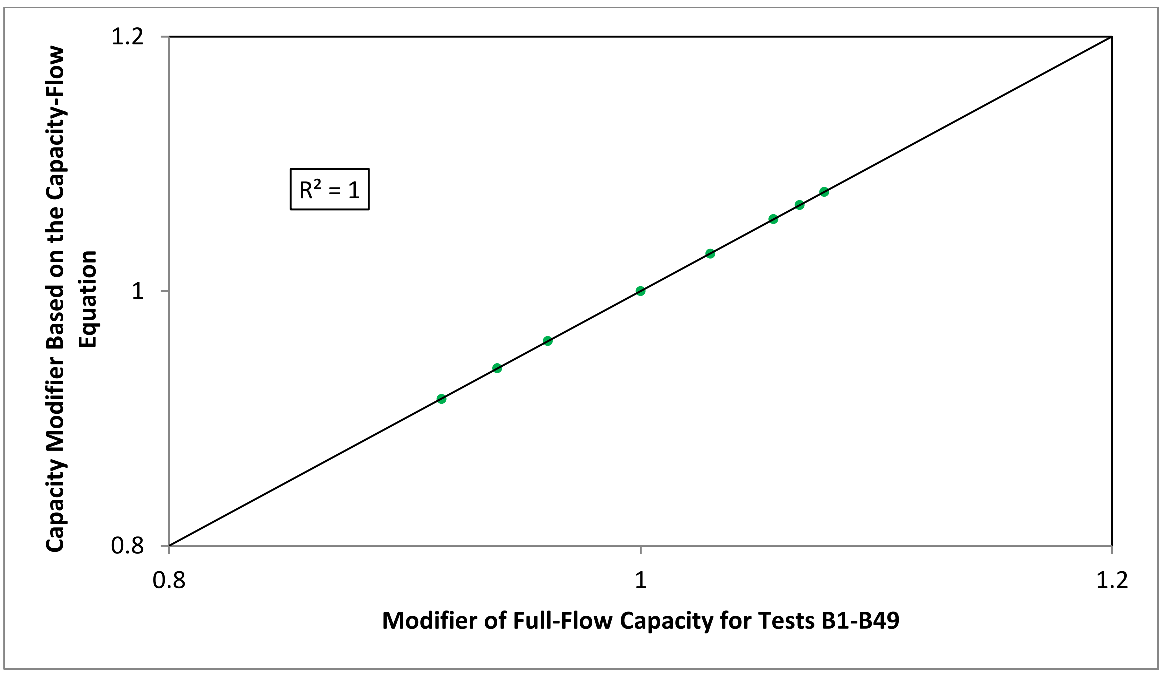

Figure 3: Comparison of predicted and measured capacity modifiers as a function of flow fraction for 48LCF014 high capacity

2.6 ENERGY INPUT RATIO MODIFIER CURVE AS A FUNCTION OF FLOW FRACTION

Table 8 shows the regression coefficients and the coefficient of determination for nine Carrier models using Equation 4. Because there are many different test temperature conditions corresponding to a given flow fraction, the EIR modifiers are averaged across those temperature conditions. The average results are used to obtain the regression coefficients. In addition, the curve coefficients in Table 8 do not distinguish between stages because the curves are very close for different stages. For all models, the regression equation fit the experimental data very well, with R^2 nearly 1 for each case. Figure 4 shows an example plot of the equation versus the test data for model 48LCF014 stage 3 (both compressors operating).

Table 8: Regression coefficients and coefficient of determination for the EIR modifier curve as a function of flow fraction (Equation 4) for each model at the high stage of operation

Model & Stage	Coefficient				R^2
	C_0	C_1	C_2	C_3	
48LCF007	1.5445	-1.0641	0.6792	-0.1601	1
48LCF008	1.7959	-1.5848	1.0367	-0.2482	1
48LCF009	1.6389	-1.2736	0.8345	-0.2002	1
48LCF012	1.7071	-1.3871	0.8903	-0.2108	1
48LCF014	1.5819	-1.1498	0.7452	-0.1776	1
48LCF017	1.6336	-1.2474	0.804	-0.1907	1
48LCF020	1.496	-0.9759	0.6294	-0.1498	1
48LCF024	1.4913	-0.9605	0.6148	-0.1458	1
48LCF026	1.5031	-0.985	0.6318	-0.1501	1
Generic Curve	1.5863	-1.1467	0.7351	-0.1745	1

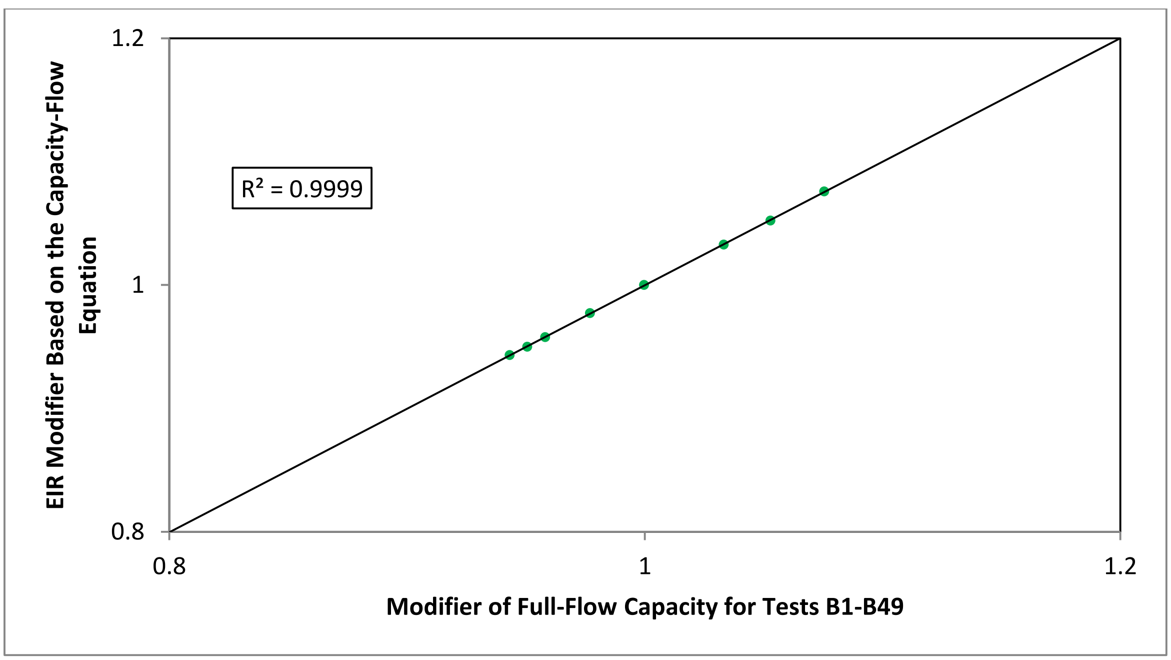

Figure 4: Comparison of predicted and measured EIR modifiers as a function of flow fraction for 48LCF014 high capacity

2.7 SUMMARY OF PERFORMANCE CURVE DEVELOPMENT

Four curves are used to characterize the WeatherExpert unit's part-load performance: the total cooling capacity as a function of indoor wet-bulb and outdoor dry-bulb temperatures, the total cooling capacity as a function of air flow fraction, efficiency as a function of indoor wet-bulb and outdoor dry-bulb temperatures, and efficiency as a function of flow fraction. These curves can be used with the EnergyPlus Object Coil:Cooling:DX:VariableSpeed to model WeatherExpert units.

The curves are generated with a wide range of the independent variables to represent the conditions experienced in RTU operation in the field:

- $12.2°C\ (54°F) \leq T_{wb,i} \leq 26.7°C\ (80°F)$
- $18.3°C\ (65F) \leq T_{c,i} \leq 51.7°C\ (125°F)$
- $0.70 \leq ff \leq 1.35$

The part-load fraction correlation as a function of part-load ratio (PLR) available in EnergyPlus models for packaged RTUs is not provided in this work because the available information is not sufficient to derive that curve. The typical PLF correlation for conventional, single-speed direct expansion (DX) cooling coils can be used and it has the following form:

$$PLF = 0.85 + 0.15 * PLR. \quad (6)$$

Although curves are provided for various WeatherExpert models, the difference between the normalized curves and the generic curve is modest (<10% in most cases). Unless the RTU size is specified, the generic curve is recommended for simulating WeatehrExpert units in EnergyPlus.

3 Building Simulation Models

Figure 5 shows the axonometric view of the big-box retail store modeled in this work. This building model is based on the stand-alone retail building prototype used to support ASHRAE Standard 90.1 development (Thornton et al. 2011). However, the footprint area was tripled to better represent big-box stores, which are deemed as a major market for RTU Challenge units. Thus, the modeled big-box store has a total floor area of 75,000 ft^2. Based on the space usage, the store is divided into five areas: front entry (0.2%), storage space (9.6%), core retail (82.4%), front retail (3.9%), and cashier area (3.9%), where the number in parenthesis indicates the percentage of that space area.

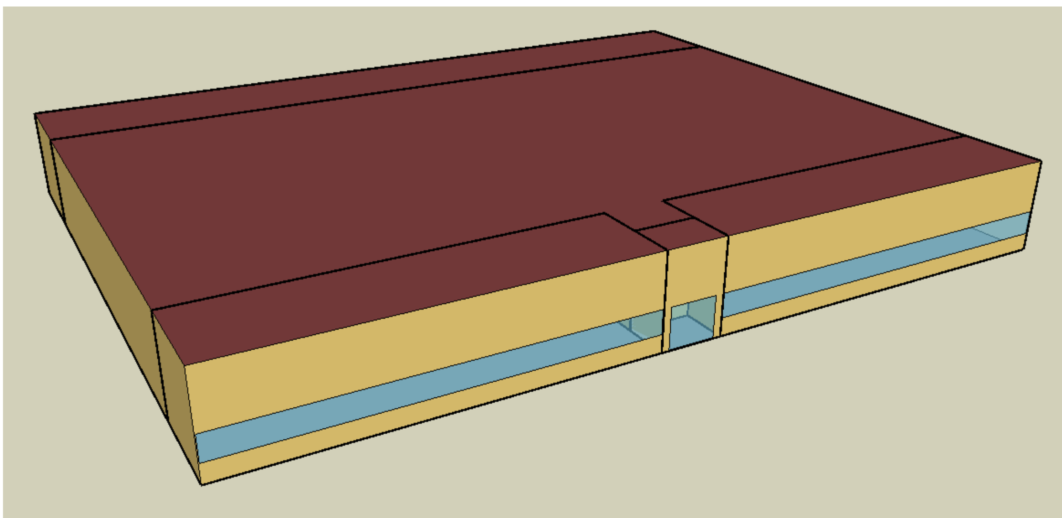

Figure 5: Axonometric view of the big-box retail store

The building model has the following opaque envelope construction elements: concrete block exterior walls, a flat roof with insulation entirely above a metal deck, and a slab-on-grade concrete floor with carpets. All exterior opaque assembly construction is configured according to Appendix A in ASHRAE Standard 90.1-2004 (ASHRAE 2004). The window construction is modeled in EnergyPlus based on the specified overall heat transfer coefficient and solar heat gain coefficient. ASHRAE Standard 90.1-2004 is followed to establish the requirements on building envelope thermal performance. The report (Thornton et al. 2011) can be referred to for more details on envelope construction and internal load profiles.

In the EnergyPlus building model, each of the five spaces is regarded as one thermal zone. Except for the front entry served by a unit heater, the other thermal zones are each equipped with a packaged unit with mechanical cooling and gas furnace heating. The packaged equipment efficiency and control strategies are discussed next.

3.1 Selection of the Packaged Equipment

In general, RTU Challenge-compliant units such as WeatherExpert are considered by building owners/designers as an option for either new construction or existing building retrofits. Other options include RTUs that just meet the Federal minimum standard or other local code requirements, such as ASHRAE Standard 90.1, or high-end RTUs that are usually available from most manufacturers' product lines. Three "references" are defined here to make the performance comparison more useful.

3.2 Reference 1

Reference 1 represents existing RTUs in the field, so it can be used as the baseline to estimate the potential of energy savings from a full upgrade to the WeatherExpert from existing equipment.

The AHRI-rated (American Heating and Refrigeration Institute) efficiency of the baseline or Reference 1 equipment performance is based on ASHRAE Standard 90.1-2004 requirement. ASHRAE 90.1-2004 specifies that for a 10-ton packaged air conditioner with gas heat, the rated energy efficiency ratio (EER) should be at least 9.9. This EER includes the supply-fan power. However, EnergyPlus models the supply fan and packaged cooling separately. Therefore, it is necessary to obtain the cooling performance excluding the supply-fan power. Deru et al. (2011) used the following equation to derive packaged equipment's coefficient of performance (COP) suitable for EnergyPlus modeling from the AHRI-rated EER:

$$\mathrm{COP} = (\frac{\mathrm{EER}}{3.413} + \mathrm{R})/(1 - \mathrm{R}) \qquad (7)$$

where R is the ratio of supply-fan power to total equipment power at the rated condition. Deru et al. (2011) used an R value of 0.12, which is a reasonable value that represents a broad class of products. Based on the laboratory test data from several products, PNNL found that using the above equation with R equal to 0.12 overestimates the COP by between 5% and 10%. Therefore, for the current work, the COP estimated from Equation 1 was adjusted.

Furthermore, the existing unit's actual performance in the field degrades with time. Therefore, it is important to apply a degradation factor to consider the actual field performance for existing RTUs. The degree of performance degradation varies with many factors such as the number of years operated in the field, number of hours of operations, weather conditions, and the level of maintenance. An arbitrary, 10% performance degradation factor was used for this work. Thus, in the EnergyPlus model, the unit's COP (excluding supply-fan energy consumption) is calculated as:

$$COP = \left(\frac{\frac{\frac{9.9}{3.413} + 0.12}{1 - 0.12}}{1.05} \right) * 0.90 = 2.94 \qquad (8)$$

In the above equation, the number 1.05 represents the adjustment factor to correct the COP overestimation; the number 0.90 represents the adjustment factor to account for the performance degradation in the field.

To estimate the annual energy consumption of the prototypical building, the RTU's part-load performance is also needed. However, because part-load performance data of existing RTUs in the field is lacking, a commercial RTU's performance data at different operating conditions were used to develop the performance curves. Because the performance curves are normalized, using the manufacturer's data to develop the curves is reasonable. The data used to develop the curves for Reference 1 equipment were provided by a manufacturer, and they represent equipment from the low-end of their product line. These curves take the standard equation forms (Equations 1-4 in Section 2.1) as used in EnergyPlus. Table 9 lists the curve coefficients used by the Reference 1 model.

Table 9: Curve coefficients for the single-stage direct expansion cooling coil in Reference 1 equipment

Coefficient	**TotCapTempModFac**	**ETRTempModFac**	**TotCapFlowModFac**	**ETRFlowModFac**
C0	0.7503	0.4152	1.0	1.0
C1	0.0161	0.0093	0.0	0.0
C2	0.0008	0.0002	0.0	0.0
C3	-0.0036	0.0150	0.0	0.0
C4	-0.0002	0.0008	—	—
C5	0.0000	-0.0018	—	—

In addition to the rated performance, RTUs compatible with Reference 1 have the following features:

- Constant-speed supply fan. When the RTU operates, its supply fan always runs at full speed (100%) regardless of the operational modes (e.g., heating, cooling, or ventilation).
- Single-stage cooling. The direct expansion (DX) cooling has one constant-speed compressor cycling on and off to meet the space cooling loads.
- Gas furnace. The gas furnace cycles on and off to meet the space heating loads.
- Integrated air-side economizer. The economizer control is modeled as differential dry-bulb temperature even though other control types such as fixed dry-bulb or enthalpy may be more common in the field or more suitable for some locations. Because economizer control is not WeatherExpert's unique feature distinguishable from conventional RTUs, the same economizer control type is used for all three references and the WeatherExpert unit.
- No demand-controlled ventilation (DCV). DCV is not WeatherExpert's unique feature distinguishable from conventional RTUs. Therefore, DCV is not modeled for all three references and the WeatherExpert unit.

3.3 Reference 2

Reference 2 represents RTUs in the market that just meet the current (2013) Federal regulations for commercial equipment standards. As a result, it can be used as the baseline to estimate the potential of energy savings from WeatherExpert units in comparison with new RTUs that meet the minimum efficiency requirements. Except for the rated full-load efficiency, RTUs compatible with Reference 2 are the same as Reference 1, and they have the following features:

- Current Federal minimum standard requires that a 10-ton packaged air conditioner with gas heat have a minimum energy efficiency ratio (EER) of 11 at rated conditions. Based on Equation 1 and using the overestimation factor of 1.05, the unit's COP excluding the supply-fan energy consumption is calculated at 3.62.

- The same performance curves developed for Reference 1 are used to model the unit's part-load performance.
- The unit has a constant-speed supply fan, as defined for Reference 1.
- The unit has single-stage DX cooling and cycles on and off to meet space cooling loads, as defined for Reference 1.
- The gas furnace cycles on and off to meet space heating loads, as defined for Reference 1.
- Integrated air-side economizer is used, as defined for Reference 1.
- No DCV is used, as explained for Reference 1.

3.4 Reference 3

Reference 3 represents the ASHRAE 90.1-2010 requirements. For RTUs with cooling capacity greater than 11,000 Btu/h, ASHRAE 90.1-2010 (ASHRAE 2010) requires two-speed fan control or variable-speed fan control. RTUs compatible with Reference 3 have the following features:

- ASHRAE requires that a 10-ton packaged air conditioner with or without gas heat has a minimum EER of 11 at rated conditions, the same as the Federal minimum standard. Based on Equation 1 and using an overestimation factor of 1.05, the unit's COP excluding the supply-fan consumption is 3.62. This COP is the efficiency at the rated conditions. A unit with fan-speed control normally has cooling capacity control to avoid coil freezing. Reference 3 models two-stage cooling, so separate sets of performance data for the two stages are needed. Because ASHRAE 90.1-2010 does not specify the 1st stage cooling efficiency, the rated COP is derived by referring to the efficiency ratio between two stages for a commercial RTU. Based on the same product used for Reference 1, the 2nd (or full) stage cooling is about 24% higher efficiency than the 1st stage cooling. Therefore, in this work, the modeled COP for 1st stage cooling is $3.62/1.24 = 2.92$.
- The curves developed for Reference 1 are used to model the unit's 2nd stage part-load performance. A new set of curves are developed for the 1st stage cooling based on the same product as used for Reference 1, but only the 1st stage cooling performance data are used. Table 10 lists the curve coefficients for the 1st stage cooling.
- Two-speed fan control is used. The supply fan has two speeds with the low speed at two thirds of the full speed. The low fan speed is used for ventilation and 1st stage DX cooling.
- Two-stage DX-cooling with equally sized constant-speed compressors is used. The switch from low stage to high stage can be based either on the space temperature deviation from the cooling set point or time lag for not reaching the cooling set point. Time lag is modeled in this work as explained later with the control sequence.
- Gas furnace cycles on and off, as defined for Reference 1.
- Integrated air-side economizer is used, as defined for Reference 1.

- No DCV is used, as explained for Reference 1.

Table 10: Curve coefficients for the 1st stage DX cooling coil in Reference 3 model

Coefficient	**TotCapTempMod Fac**	**ETRTempMod Fac**	**TotCapFlowMod Fac**	**ETRFlowMod Fac**
C0	0.8499	0.6649	1.0	1.0
C1	0.0176	-0.0263	0.0	0.0
C2	0.0010	0.0019	0.0	0.0
C3	-0.0088	0.0204	0.0	0.0
C4	-0.0002	0.0011	—	—
C5	0.0000	-0.0028	—	—

3.5 RTU Challenge Unit: Carrier WeatherExpert

In comparison with the above three reference units, a WeatherExpert unit has the following features:

- The rated COP excluding the supply-fan power was calculated for all three stages for each of the nine product models in Table 1. The average rated COP across all nine product models was calculated as 4.80, 4.59, and 4.09, respectively, for the 1st, the 2nd, and the 3rd DX cooling stage. These numbers are used in the simulation.
- The generic performance curves presented in Section 2 are used in the simulation to capture the WeatherExpert unit's part-load performance.
- Integrated air-side economizer is used, as defined for Reference 1.
- No DCV is used, as explained for Reference 1.
- The detailed control sequence used to model the WeatherExpert unit's operation is described next in Section 4.

4 ENERGY MANAGEMENT SYSTEM (EMS) IMPLEMENTATION

To accurately model the sequence of operation of the WeatherExpert unit, the EMS feature in EnergyPlus is used to customize the sequence of operations. The EMS provides a variety of sensors and actuators much like an actual building automation system. The sequence of operations embedded in the EnergyPlus input files is used to override the traditional EnergyPlus control and to add the desired control functionality into the simulation.

Depending on the space temperature T, the RTU has four basic operation modes: idle, ventilation, heating, and cooling.

Idle mode. The RTU is in the idle mode if 1) the space temperature lies between the heating and cooling set points, and 2) the space is unoccupied. In the idle mode, the fan, the heating and the cooling are all off. Note that the heating and cooling set points during occupied and unoccupied modes may be different.

Ventilation mode. The RTU operates in the ventilation mode if 1) the space temperature lies between the heating and cooling set points, and 2) the space is scheduled to be occupied.

Heating mode. The RTU operates in the heating mode if the space temperature is less than the heating set point. Once heating is initiated, it continues until the space temperature rises above the heating set point plus a differential (e.g., 1.8°F).

Cooling mode. The RTU operates in the cooling mode if the space temperature is greater than the cooling set point. Depending on whether the outdoor air is favorable for cooling, the following control sequence is used to model WeatherExpert unit's operation.

When outdoor air is favorable for cooling:

- 1st stage cooling call. The unit initiates the 1st stage economizing mode: the supply fan runs at 67% of its full speed; both compressors are off; the outdoor air (OA) damper is modulated to meet mixed-air temperature set point at 55°F. After running in this mode (1st stage economizing) for 5 minutes, the unit will:
    - Continue this mode as long as $T_{CoolSP} - \delta_{Cool} \leq T \leq T_{CoolSP}$, where T_{CoolSP} is the cooling set point, and δ_{Cool} is the cooling differential;
    - Finish this mode and switch to the ventilation mode if $T < T_{CoolSP} - \delta_{Cool}$;
    - Initiate the 2nd stage cooling call if $T > T_{CoolSP}$.
- 2nd stage cooling call.
  First, the unit runs in the 2nd stage economizing mode: the supply fan runs at its full speed; compressors are still off; the OA damper is fully open. After running in this mode (2nd stage economizing) for 5 minutes, the unit will:
    - Continue this mode as long as $T_{CoolSP} - \delta_{Cool} \leq T \leq T_{CoolSP}$;
    - Finish this mode and switch to the ventilation mode if $T < T_{CoolSP} - \delta_{Cool}$;
    - Initiate the 1st stage mechanical cooling (compressor A only) if $T > T_{CoolSP}$.

  In the 1st stage mechanical cooling mode, the low-capacity compressor is on, the supply fan runs at 67% of its full speed. After running in this mode (1st stage mechanical cooling) for 5 minutes, the unit will:

- Continue this mode as long as $T_{CoolSP} - \delta_{Cool} \le T \le T_{CoolSP}$;
  - Finish this mode and switch to the ventilation mode if $T < T_{CoolSP} - \delta_{Cool}$;
  - Initiate the 3rd stage cooling call if $T > T_{CoolSP}$.
- 3rd stage cooling call.
  First, the unit runs in the 2nd stage mechanical cooling mode: the high-capacity compressor is on; the supply fan runs at 67% of its full speed; the OA damper is fully open. After running in this mode (2nd stage mechanical cooling) for 5 minutes, the unit will:
  - Continue this mode as long as $T_{CoolSP} - \delta_{Cool} \le T \le T_{CoolSP}$;
  - Finish this mode and switch to the ventilation mode if $T < T_{CoolSP} - \delta_{Cool}$;
  - Initiate the 3rd stage mechanical cooling (compressor A&B) if $T > T_{CoolSP}$.

  In the 3rd stage mechanical cooling mode, both the low- and high-capacity compressors are on, and the supply fan runs at its full speed. The unit will:
  - Continue this mode as long as $T_{CoolSP} - \delta_{Cool} \le T \le T_{CoolSP}$;
  - Finish this mode and switch to the ventilation mode if $T < T_{CoolSP} - \delta_{Cool}$.

When outdoor air is not favorable for cooling:

- 1st stage cooling call. The unit runs in the 1st stage mechanical cooling mode: the low-capacity compressor is on, the supply fan runs at 67% of its full speed; OA damper is at the minimum. After running in this mode (1st stage mechanical cooling) for 5 minutes, the unit will:
  - Continue this mode as long as $T_{CoolSP} - \delta_{Cool} \le T \le T_{CoolSP}$;
  - Finish this mode and switch to the ventilation mode if $T < T_{CoolSP} - \delta_{Cool}$;
  - Initiate the 2nd stage cooling call if $T > T_{CoolSP}$.
- 2nd stage cooling call. The unit runs in the 2nd stage mechanical cooling mode: the high-capacity compressor is on, the supply fan is running at 67% of its full speed; OA damper is at the minimum. After running in this mode (2nd stage mechanical cooling) for 5 minutes, the unit will:
  - Continue this mode as long as $T_{CoolSP} - \delta_{Cool} \le T \le T_{CoolSP}$;
  - Finish this mode and switch to the ventilation mode if $T < T_{CoolSP} - \delta_{Cool}$;
  - Initiate the 3rd stage cooling call if $T > T_{CoolSP}$.
- 3rd stage cooling call. The unit runs in the 3rd stage mechanical cooling mode: both the low- and high-capacity compressors are on, the supply fan is running at its full speed, OA damper is at the minimum. The unit will:
  - Continue this mode as long as $T_{CoolSP} - \delta_{Cool} \le T \le T_{CoolSP}$;
  - Finish this mode and switch to the ventilation mode if $T < T_{CoolSP} - \delta_{Cool}$.

5 EnergyPlus Simulation Results

The EnergyPlus simulation models were run for three locations: Houston, Los Angeles, and Chicago. Both HVAC energy savings and cost savings are presented in this section.

5.1 Energy Savings

Table 11 shows the energy end uses including cooling energy (kWh), fan energy (kWh), heating energy (Therm), total RTU electricity (kWh), and total RTU energy (MMBtu). Figure 6 shows the RTU electricity savings is determined for the three locations from using the WeatherExpert units in comparison with the three reference units for the whole building. Figure 7 shows the total RTU energy savings (including both electricity savings and natural gas penalties). Both figures have two parts: the top part shows the percentage of savings and the bottom part shows the absolute savings.

Table 11: Simulated annual HVAC energy end uses for the modeled retail building

Location	RTU Type	Cooling (kWh)	Fan (kWh)	Heating (Therm)	Total RTU Electricity (kWh)	Total RTU Energy (MMBtu)
Houston	Reference 1	268,311	152,731	3,314	421,042	1,768
	Reference 2	218,178	152,731	3,314	370,908	1,597
	Reference 3	220,567	73,356	3,872	293,922	1,390
	WeatherExpert	160,314	48,983	4,140	209,297	1,128
Los Angeles	Reference 1	91,767	131,683	1,222	223,450	885
	Reference 2	74,619	131,683	1,222	206,303	826
	Reference 3	81,475	68,406	1,575	149,881	669
	WeatherExpert	52,344	40,492	1,758	92,836	493
Chicago	Reference 1	102,939	147,956	11,763	250,894	2,032
	Reference 2	83,706	147,956	11,763	231,661	1,967
	Reference 3	85,808	70,472	13,264	156,281	1,860
	WeatherExpert	57,761	40,869	13,980	98,631	1,735

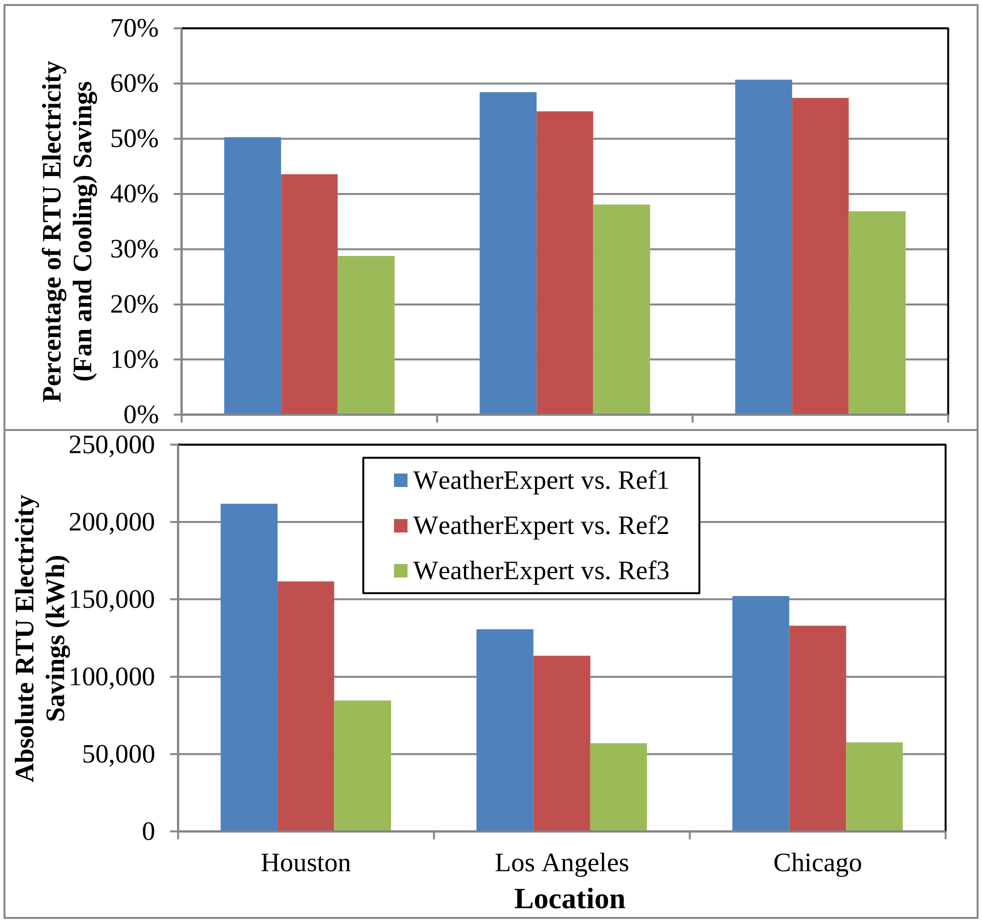

Figure 6: Annual RTU electricity savings from the use of WeatherExpert units compared to the three reference units for the modeled retail building

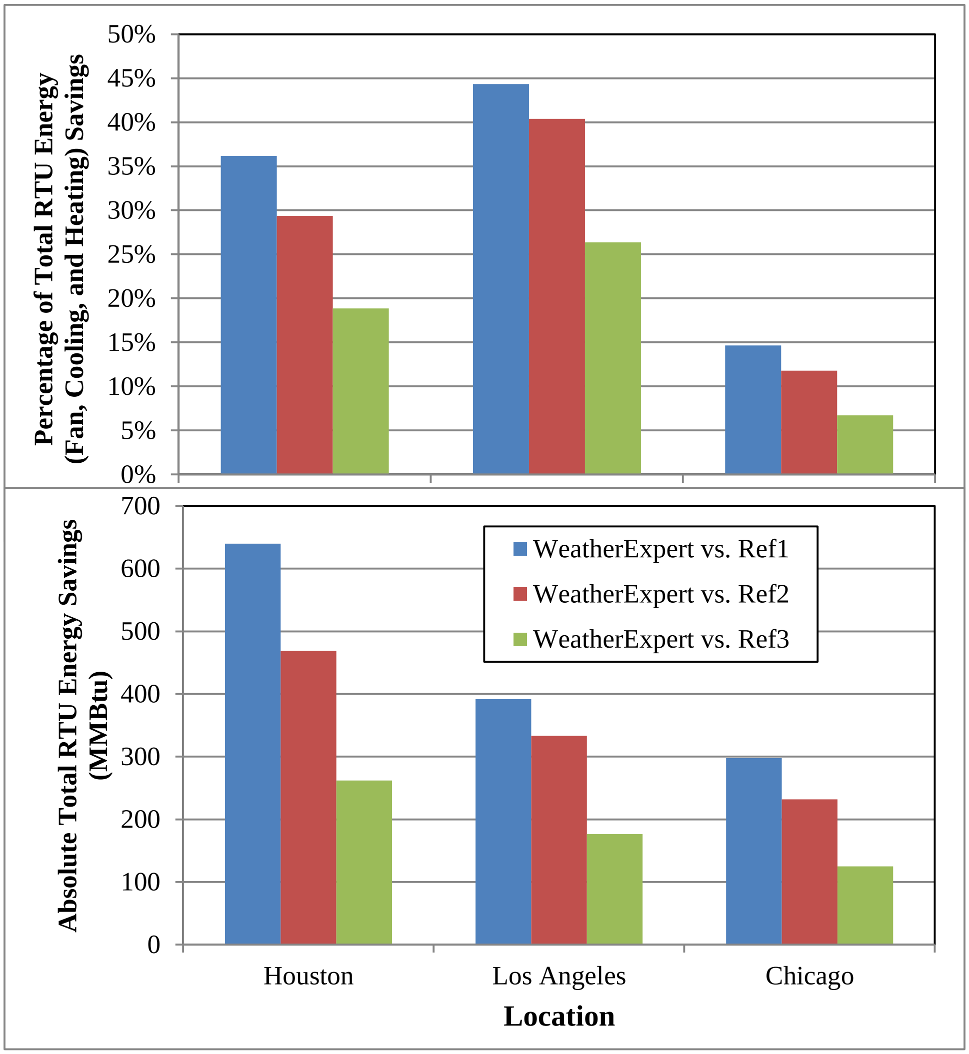

Figure 7: Annual RTU total energy savings from the use of WeatherExpert units compared to the three reference units for the modeled retail building

Table 11, Figure 6 and Figure 7 lead to the following conclusions:

- Using Reference 1 as the baseline, the WeatherExpert unit consumes 36% less HVAC energy (including electricity for fan and cooling and natural gas for heating) in Houston, 44% in Los Angeles, and 15% in Chicago. The WeatherExpert unit saves more than 50% RTU electricity consumption in all three locations. The electricity savings come from the higher cooling efficiency of WeatherExpert units and the use of supply-fan speed control. Table 11 shows that the fan energy savings are more than cooling energy savings in both Los Angeles and Chicago. Because the supply-fan energy was simulated as heat gain to the supply-air stream, reducing fan energy also leads to an increase in heating energy consumption.
- Using Reference 2 as the baseline, the WeatherExpert unit consumes 29% less HVAC energy in Houston, 40% less in Los Angeles, and 12% less in Chicago. The WeatherExpert unit saves about 44% RTU electricity consumption in Houston and about 55% in both Los Angeles and Chicago. Because both Reference 2 and Reference 1 have

constant-speed supply fans, the fan savings remain the same after the baseline changes from Reference 1 to Reference 2.

- Using Reference 3 as the baseline, the WeatherExpert unit consumes 19% less HVAC energy in Houston, 26% less in Los Angeles, and 7% less in Chicago. The WeatherExpert unit saves about 29% RTU electricity consumption in Houston and about 37% in both Los Angeles and Chicago.

5.2 Cost Savings

Average blended gas and electricity prices from EIA (2013) are used for the analysis. Table 12 provides the 2012 electricity and natural gas prices for the three locations. Based on these prices and the energy simulation results from Table 11, energy costs are calculated as shown in Table 13. Figure 8 shows the RTU electricity cost savings in the three locations from using the WeatherExpert units in comparison with the three reference units for the whole building. Figure 9 shows the total RTU energy cost savings (including both electricity cost savings and natural gas cost penalties).

Table 12: Electricity and natural gas prices by locations

Location	Electricity ($/kWh)	Natural Gas ($/Therm)
Houston	0.081	0.707
Los Angeles	0.126	0.713
Chicago	0.079	0.779

Table 13: Annual HVAC energy costs of the modeled retail building

Location	RTU Type	Cooling Energy Cost ($)	Fan Energy Cost ($)	Heating Energy Cost ($)	Total RTU Electricity Cost ($)	Total RTU Energy Cost ($)
Houston	Reference 1	21,733	12,371	2,343	34,104	36,447
	Reference 2	17,672	12,371	2,343	30,044	32,387
	Reference 3	17,866	5,942	2,738	23,808	26,545
	WeatherExpert	12,985	3,968	2,927	16,953	19,880
Los Angeles	Reference 1	11,563	16,592	871	28,155	29,026
	Reference 2	9,402	16,592	871	25,994	26,865
	Reference 3	10,266	8,619	1,123	18,885	20,008
	WeatherExpert	6,595	5,102	1,254	11,697	12,951
Chicago	Reference 1	8,132	11,688	9,163	19,821	28,984
	Reference 2	6,613	11,688	9,163	18,301	27,464
	Reference 3	6,779	5,567	10,332	12,346	22,679
	WeatherExpert	4,563	3,229	10,891	7,792	18,683

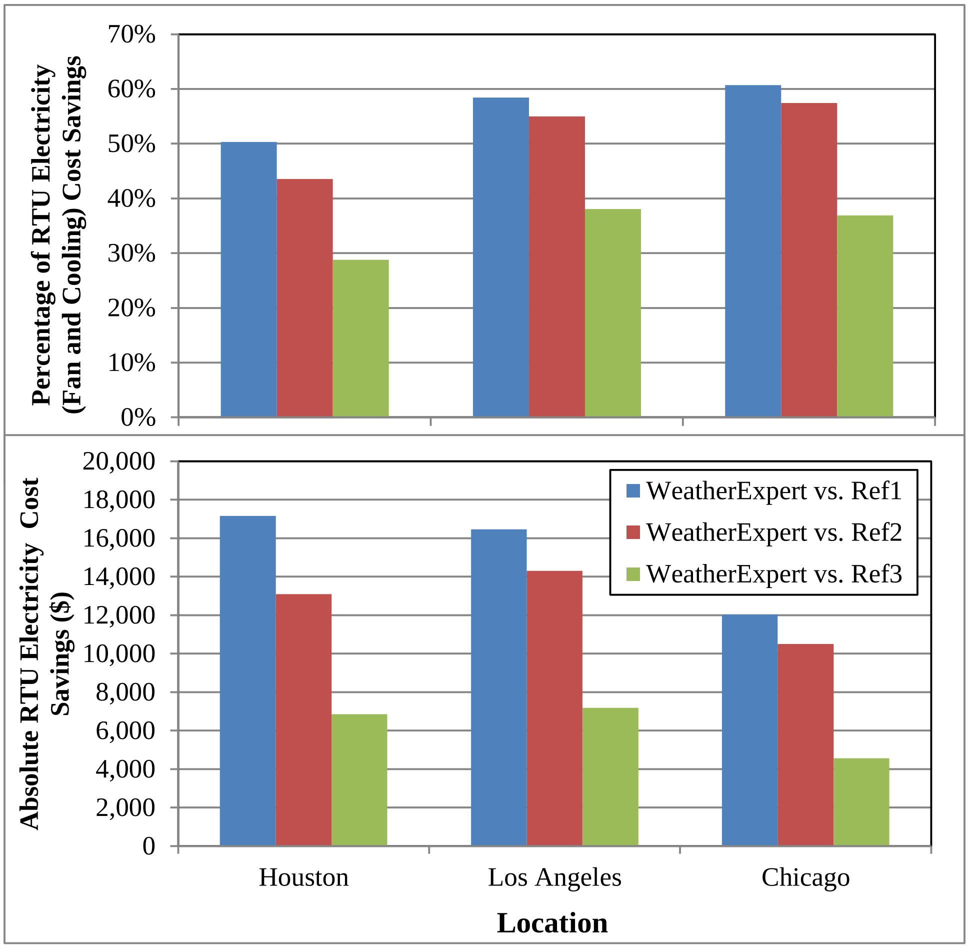

Figure 8: Annual RTU electricity cost savings from the use of WeatherExpert units compared to the three reference units for the modeled retail building

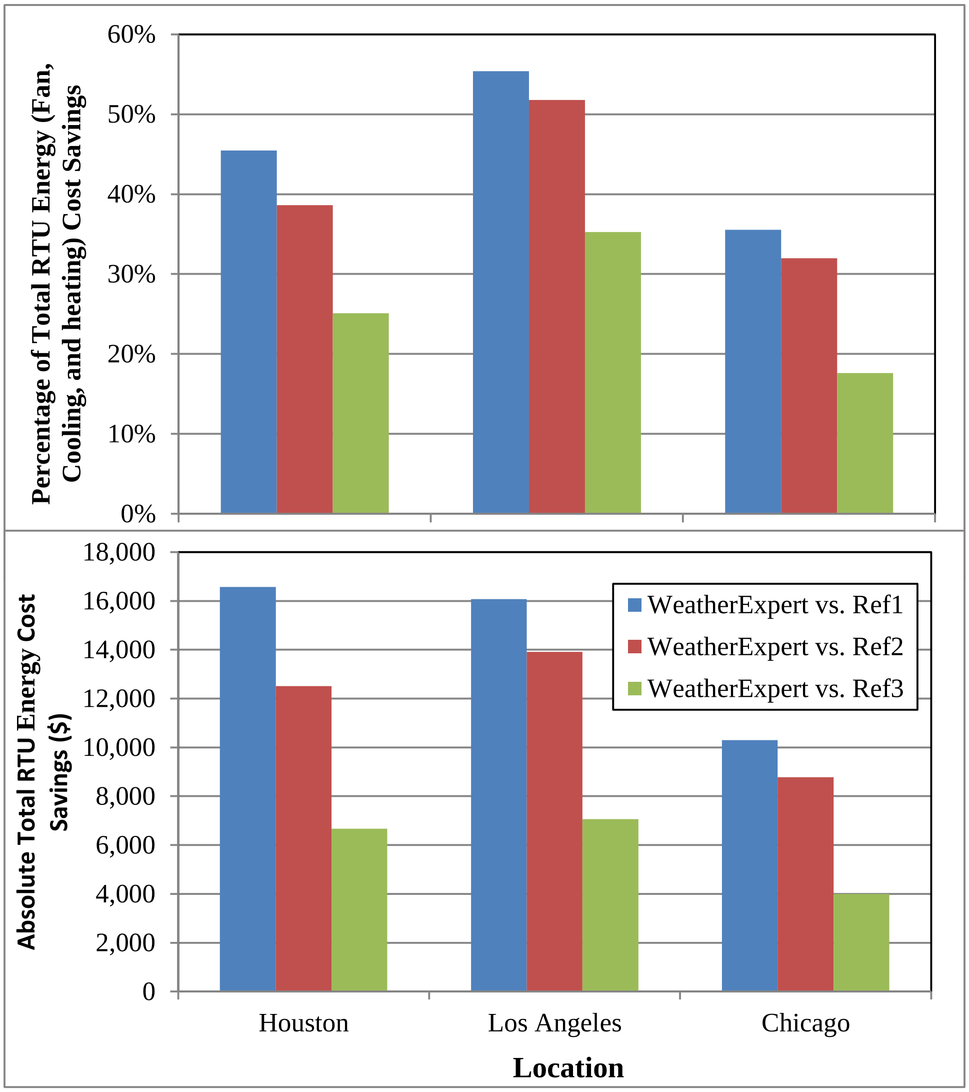

Figure 9: Annual RTU total energy cost savings from the use of WeatherExpert units compared to the three reference units for the modeled retail building

Table 13, Figure 8 and Figure 9 lead to the following conclusions:

- Using Reference 1 as the baseline, WeatherExpert units lead to about 45% lower HVAC energy cost in Houston, 55% lower cost in Los Angeles, and 35% lower cost in Chicago. The percentage savings of electricity cost is more than 50% for all three locations.
- Using Reference 2 as the baseline, WeatherExpert units lead to about 39% lower HVAC energy cost in Houston, 52% lower cost in Los Angeles, and 32% lower cost in Chicago. The percentage savings of electricity cost is 44%, 55%, and 57%, respectively in the above three locations.
- Using Reference 3 as the baseline, WeatherExpert units lead to about 25% lower HVAC energy cost in Houston, 35% lower cost in Los Angeles, and 18% lower cost in Chicago. The percentage savings of electricity cost is 29%, 38%, and 37%, respectively in the above three locations.

In summary,

Table 14 provides a summary of the energy and cost savings in both relative and absolute terms. For natural gas savings and electricity savings, there is only one fuel type involved in the calculation of percentage savings. Therefore, the percentage savings are the same for energy and cost. However, because there are mixed fuel types in total savings, the percentage savings needs to be distinguished between energy and cost, as shown in the table.

Table 14: Summary of annual energy and cost savings for the modeled retail building

	Natural Gas Savings			**Electricity Savings**			**Total Savings**			
Location	**%**	**Therm**	**$**	**%**	**kWh**	**$**	**% Energy**	**% Cost**	**MMBtu**	**$**
WeatherExpert[#] (EER= 13.0, IEER* = 20.8) vs. Reference 1 (EER= 8.9, IEER = 12.8)										
Houston	-25	-825	-584	50	211,744	17,151	36	45	640	16,568
Los Angeles	-44	-536	-382	58	130,614	16,457	44	55	392	16,075
Chicago	-19	-2,218	-1,728	61	152,264	12,029	15	36	298	10,301
WeatherExpert (EER= 13.1, IEER = 20.8) vs. Reference 2 (EER= 11.0, IEER = 12.8)										
Houston	-25	-825	-584	44	161,611	13,091	29	39	469	12,507
Los Angeles	-44	-536	-382	55	113,467	14,297	40	52	334	13,914
Chicago	-19	-2,218	-1,728	57	133,031	10,509	12	32	232	8,782
WeatherExpert (EER= 13.0, IEER = 20.8) vs. Reference 3 (EER= 11.0, IEER = 12.8)										
Houston	-7	-267	-189	29	84,625	6,855	19	25	262	6,666
Los Angeles	-12	-183	-131	38	57,044	7,188	26	35	176	7,057
Chicago	-5	-717	-558	37	57,650	4,554	6.7	17.6	125	3,996

*IEER = Integrated energy efficiency ratio

[#] EER and IEER for WeatherExpert units are from the AHRI published ratings for a 10-ton unit

6 DISCUSSION

In this performance assessment of WeatherExpert units, efforts were focused on those features that lead to cooling and fan energy savings. Gas furnace performance including both rated full-load and part-load efficiency was kept the same across all compared RTUs. As a result, the savings will be underestimated if WeatherExpert improves heating efficiency relative to conventional air conditioners.

The Reference 1 model uses the performance curves developed for new equipment from a manufacturer's low-end product line. Existing RTUs in the field may have degraded part-load performance as well. Therefore, the energy and cost savings are likely underestimated when Reference 1 is used to approximate existing RTUs. Similarly, the product, upon which the performance curves was developed, has an IEER of 11.8, which is higher than the ASHRAE 90.1-2010 minimum IEER requirement of 11.0. Higher savings are expected if performance curves in References 2 and 3 closely match the minimum codes and standards requirements.

Based on the simulation results, the RTU Challenge unit, if widely adopted, could lead to significant energy, cost and emission reductions. Because the cost of these units was not available and because the costs would be specific to a given installation, no attempt was made to estimate the potential payback periods associated with any of the three reference scenarios. However, if the incremental cost for any of the three reference cases is known, one can easily estimate a simple payback period.

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