



# **Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program**

**California Energy Commission  
Contract # 500-03-030**

## ***Project 4: Advanced Rooftop Unit***

***Deliverable D4.3d – DRAFT 3***

## ***ARTU Cost Benefit Analysis***

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# Advanced Packaged Rooftop Unit (ARTU) Project

## Task 4.3: ARTU Cost Benefit Analysis

### Table of Contents

1.0	Executive Summary.....	1
2.0	Introduction.....	4
2.1	General Information.....	4
3.0	Cost-Benefit Analysis.....	6
3.1	Physical Hardware.....	9
3.1.1	Operational Performance .....	9
3.1.2	Maintenance and Serviceability .....	17
3.1.3	Reliability and Robustness.....	19
3.2	Diagnostics and Monitoring .....	21
4.0	Conclusions.....	22
5.0	References .....	23

## **Preface**

Architectural Energy Corporation (AEC), an energy and environmental research, development, and design consulting firm located in Boulder, Colorado, submits this document to the California Energy Commission (CEC) as part of the Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program, Project 4: Advanced Packaged Rooftop Unit. The CEC Contract Manager is Chris Scruton. The AEC Program Director is Vernon Smith. The AEC Project Manager is Douglas Dougherty.

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## 1.0 Executive Summary

This project is part of a California Energy Commission program within the Public Interest Energy Research program (PIER) known as the “Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program” (FDD program).

This document presents an analysis of the costs and benefits associated with the features related to an advanced rooftop unit (ARTU). These 36 features were identified in the “ARTU Product Definition Report” (AEC 2005) and relate to the following:

- Economizer section
- Fan and unit cooling efficiency
- Refrigerant type
- Fan and refrigeration control
- Thermostat and sensors
- Refrigeration section serviceability
- Diagnostics and monitoring

The 36 ARTU features are divided into four groups in this report:

- Operational Performance
- Maintenance and Serviceability
- Reliability and Robustness
- Diagnostics and Monitoring

The costs and benefits in this report relate to a 5-ton electric cooling, gas heating rooftop unit, a common HVAC system found in small commercial installations.

For this analysis, a basic “off the shelf” rooftop unit, called the “baseline RTU”, is compared with a rooftop unit that incorporates all of the ARTU features, called the “ARTU”.

### Costs

The costs of the baseline RTU and ARTU are based on costs for two different 5-ton Carrier rooftop units: one that matches the baseline RTU, and one that matches the ARTU. The costs related to the advanced fault detection and diagnostics features not already included in the ARTU were obtained from other studies (Li-Braun 2007, AEC 2005).

#### *Cost Summary*

<b>Unit</b>	<b>Installed Cost</b>
Baseline RTU	\$5,700
ARTU	\$9,800

Benefits

Both energy and non-energy benefits are realized by adding the ARTU features to the baseline RTU. The energy-related benefits were estimated using the following methods:

- Modeling a simple retail building using eQUEST, a DOE-2 building energy use simulation. Simulations were performed for three locations in California with different climates (San Diego, Sacramento, and Palm Springs); the building in each city was sized to match the cooling capacity of the 5-ton baseline RTU. The energy use outputs for each city were then averaged. With the building characteristics fixed, the HVAC system was then changed to simulate the ARTU features and the simulations were rerun. The energy benefits for 14 of the 29 energy-related ARTU features were estimated through the use of these energy simulations.
- Incorporating energy use data from previous research related to small packaged RTUs (Jacobs 2003).

Some of the energy benefits relate to avoided energy cost. For example, the annual energy cost for operating a rooftop unit with an improper refrigerant charge is, on average, \$12 more than the energy cost for a properly charged rooftop unit. This \$12 is included in the energy-related benefits, since incorporating the ARTU feature related to self-monitoring refrigerant charge through advanced diagnostics (feature 11-05) would help to keep the unit operating at the proper charge.

The non-energy benefits of the ARTU features relate to annual saved service time. For example, the feature related to locating the refrigerant pressure ports outside the condenser fan plenum (feature 9-03) is estimated to save one hour (\$90) of service time per year, since the condenser fan plenum will not have to be removed and replaced each time these refrigerant pressures are measured. The non-energy benefits of the ARTU features apply to those located in the Maintenance and Serviceability group.

*Benefits Summary*

<b>Group or Sub-Group</b>	<b>Number of ARTU Features</b>	<b>Annual Energy Benefit</b>	<b>Annual Non-Energy Benefit</b>
Physical Hardware			
Operational Performance	18	\$240	
Maintenance and Serviceability	7		\$200
Reliability and Robustness	8	\$30 - \$260	
Diagnostics and Monitoring	3	\$30	\$100
Subtotals		\$300 - \$530	\$300
Total	36	\$600 - \$830	

Summary

The estimated total cost for incorporating the 36 ARTU features into a basic 5-ton rooftop unit is \$4,100. The estimated annual combined energy and non-energy benefit related to the ARTU features is between \$600 and \$830. This gives an estimated simple payback time of between 4.9 and 6.9 years.

## 2.0 Introduction

### 2.1 General Information

Architectural Energy Corporation is administering a program for the California Energy Commission's "Public Interest Energy Research" program (PIER), known as the "Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program" (FDD program).

One of the projects within the FDD program is Project 4, "Advanced Packaged Rooftop Unit (ARTU)". The ARTU project builds on previous research conducted under NBI PIER Element 4, Integrated Design of Small Commercial HVAC Systems (CEC Contract 400-99-012). That program published results of field studies in which more than 200 rooftop units, none of which were more than four years old, were surveyed. These units, despite their young age, exhibited a number of problems, including poor economizer operation, improper refrigerant charge, low air flow, high fan power and cycling fans, and other control issues. Such issues often go undetected by building owners and even service personnel.

That program also produced performance guidance for designers and operators on ways to improve the efficiency and operations of small package HVAC units. Many of these improvements could be integrated into a new "advanced" unit that would directly address performance and market impact objectives.

The present project developed and tested an ARTU prototype with a 5 ton cooling capacity that addresses these problems in small commercial building mechanical systems, and the resulting energy impacts and ventilation problems (IEQ) that result from poorly controlled or out-of-tolerance systems, and from lack of notification when a problem occurs.

The project team, with input from members of the project's Technical Advisory Group (TAG), developed a list of product features that an ARTU should have, and that incorporating these features in a demonstration rooftop unit would provide value to the manufacturing, contracting, utility and energy communities. These features are grouped in the following categories:

- Economizer Improvements
- Fan Improvements
- Unit Efficiency
- Refrigeration Cycle Improvements
- Fan Controls
- Refrigerant Control
- Thermostat Capability
- Sensors
- Installation & Check-out Capability
- Advanced Monitoring
- Advanced Diagnostics

Details of the feature definitions and discussions of the reasoning behind their selections are found in a previously issued document, the “ARTU Product Definition Report” (AEC 2005).

An important aspect of new or improved product is, of course, cost. It does no good to define requirements for product improvements if they are too costly to implement on a wide scale. Therefore, a cost-benefit analysis was developed for the ARTU, and the results of that analysis are presented in the body of this document.

### 3.0 Cost-Benefit Analysis

This section includes an overall summary of the cost-benefit analysis for the 36 Level 1 and 2 ARTU features. The following sections contain more detailed discussions for each feature and group of features.

#### Costs

During the testing phase of the ARTU project, a 5-ton Carrier rooftop unit, Carrier model 48PG (“Centurion” series), was tested at Southern California Edison’s Refrigeration & Thermal Test Center. This unit includes many ARTU features, and is Carrier’s premium rooftop unit. As a baseline for estimating the costs related to adding the ARTU features to a basic rooftop unit, estimated contractor’s costs for the 5-ton Carrier 48PG and a 5-ton Carrier 48HJ (a more basic rooftop unit that has only a few ARTU features and that just meets ASHRAE 90.1-2004 energy efficiency requirements) were obtained from a Carrier representative in Portland, Oregon. These Carrier units include the following:

*Table 1. Carrier Rooftop Unit Comparison*

<b>Component</b>	<b>Carrier 48HJ (“Baseline RTU”)</b>	<b>Carrier 48PG (“ARTU”)</b>
Cooling efficiency	SEER 13	SEER 14
Heating efficiency	81% steady-state thermal efficiency	81% steady-state thermal efficiency
Control	Electro-mechanical	Microprocessor-based
Economizer	<ul style="list-style-type: none"> <li>• Field-installed</li> <li>• Non-integrated</li> <li>• Single point temperature-based control</li> <li>• One year standard warranty</li> </ul>	<ul style="list-style-type: none"> <li>• Factory-installed</li> <li>• Integrated</li> <li>• Differential enthalpy-based control</li> <li>• Five-year warranty</li> </ul>
Thermostat	<ul style="list-style-type: none"> <li>• Residential-style</li> <li>• Programmable</li> </ul>	<ul style="list-style-type: none"> <li>• Commercial-style</li> <li>• Programmable</li> <li>• With CO<sub>2</sub> sensor</li> </ul>
Refrigerant	R-22	R-410A

The Carrier 48PG includes additional features not included in the ARTU list of features, so the 48PG cost may be higher than the cost of a basic rooftop unit with ARTU features added. These additional features include a slide out fan assembly for cleaning and motor change ease, a slide out condensate pan for cleaning, and access ports for condenser coil cleaning. Also, the Carrier 48HJ unit already includes a few ARTU features, e.g., 8-03 (sensors that are not polarity sensitive are used) and 9-04 (controls to adjust minimum outside air position are accessible with air plenum panels in place). For this analysis, a

10% deduct to the 48PG material cost is applied to account for features included in the unit that are beyond the list of ARTU features and a 10% deduct to the 48HJ material cost is applied to account for ARTU features already included in this unit. Note, however, that the labor to install a unit and the contractor overhead and profit values will not change despite the 10% reduction in material costs. Therefore, the overall reduction in *installed* costs has been estimated at approximately 9.2%. The feature-specific discussions in the following sections include details regarding the latter, where the Carrier 48HJ already includes ARTU features.

Installed cost estimates for the after-factory ARTU features related to advanced fault detection and diagnostics (FDD) range from \$250-\$600 (Li-Braun 2007) to \$500 (AEC 2005, assuming four rooftop units per site). However, the Carrier 48PG unit already has approximately 70% of the recommended FDD features installed as part of the control package. Therefore, an additional \$150 cost has been applied to account for the enhanced FDD features not already included in the Carrier 48PG unit.

*Table 2. Cost Summary*

<b>Unit</b>	<b>Base Installed Cost</b>	<b>Final Installed Cost*</b>
Baseline RTU (based on Carrier 48HJ)	\$6,200	<b>\$5,700</b>
ARTU (based on Carrier 48PG)	\$10,500	<b>\$9,800</b>
<b>Cost Differential</b>		<b>\$4,100</b>

\* Baseline RTU includes 9.2% installed cost deduct to account for ARTU material features already included in Carrier 48HJ model. ARTU includes 9.2% installed cost deduct to account for Carrier 48PG material features beyond current list of ARTU features, as well as \$150 for enhanced FDD features.

The installed costs shown in Table 2 include material, labor, installing contractor’s overhead and profit, general contractor’s mark-up, and a factor to adjust costs to California for a 5-ton electric cooling, gas heating rooftop unit with controls and an airside economizer section. Labor, overhead and profit, and local cost adjustment values were estimated based on an industry-standard cost estimating guide (RSMMeans 2007). The Carrier 48PG costs also include the \$150 material cost related to the enhanced FDD-related ARTU features not currently installed on the 48PG unit. As indicated in the table, the difference in installed cost between the baseline RTU and the ARTU is \$4,100.

Benefits

Both energy and non-energy benefits are realized by adding ARTU features to the baseline RTU. The cumulative benefit for all of the ARTU features will be lower than the sum of the individual ARTU feature benefits due to the overlap between features. For example, the benefits related to features 1-01 (factory-installed economizer), 1-02 (direct drive modulating economizer actuator, gear driven economizer interconnections, and permanently lubricated bushings or bearings on economizer dampers), and 1-08 (economizer systems factory warranted for five years) include energy savings related to a fully functioning economizer. Summing these benefits would give exaggerated savings estimates.

The estimated annual energy and non-energy savings related to the cumulative ARTU features are summarized in the following table. These savings are averaged over a number of units, and would not necessarily apply to one individual unit. For example, the savings related to a fully functioning economizer (Reliability & Robustness sub-group) is based on research that found 63% of installed rooftop units operating with a failed economizer; this would not be the savings seen by any one particular unit, but would be a site average.

*Table 3. Benefits Summary*

<b>Group or Sub-Group</b>	<b>ARTU Features</b>	<b>Annual Energy Benefit</b>	<b>Annual Non-Energy Benefit</b>
Physical Hardware			
Operational Performance	1-03, 1-04, 1-05, 1-07, 1-09, 2-01, 3-01, 4-01, 4-02, 5-01, 5-02, 6-01, 7-01, 7-02, 7-03, 8-01, 8-04, 11-01	\$240	
Maintenance and Serviceability	9-01, 9-02, 9-03, 9-04, 10-01, 10-02, 10-03		\$200
Reliability and Robustness	1-01, 1-02, 1-06, 1-08, 8-02, 8-03, 11-02, 11-03	\$30 - \$260	
Diagnostics and Monitoring	11-04, 11-05, 11-06	\$30	\$100
<b>Subtotals</b>		<b>\$300 - \$530</b>	<b>\$300</b>
<b>Total</b>		<b>\$600 - \$830</b>	

The ARTU features are divided into two main groups: Physical Hardware and Diagnostics and Monitoring. A more detailed benefit analysis for each feature and group of features is included in the following sections.

### 3.1 Physical Hardware

This group contains ARTU features that are physically inherent to the unit and that relate to its control. Three sub-groups are included in this group:

- Operational Performance
- Maintenance and Serviceability
- Reliability and Robustness

#### 3.1.1 Operational Performance

This section includes a more detailed discussion of the ARTU features that relate to the operational performance of the rooftop unit.

Energy savings estimates related to some of the ARTU features in this group are based on output from eQUEST, a DOE-2 building energy use simulation program, for a simple building. The building model is not complex; the simulations were performed only to obtain a rough estimate of energy savings. Building simulations were performed for three major population centers in California with different climate zones:

*Table 4. Cities Used in Energy Use Simulations*

City	CEC Climate Zone	Cooling Degree Days (65°F base)	Heating Degree Days (65°F base)
San Diego	7	866	1,063
Sacramento	12	1,248	2,666
Palm Springs	15	4,224	951

The modeled building is a small single-story retail building with the following characteristics, using default eQUEST values wherever reasonable:

- Square floor plan with a 10' high lay-in acoustic tile ceiling and 14' high roof. Floor plan dimensions vary for each of the three cities, to match the cooling capacity of a standard 5-ton rooftop unit.
- Metal frame roof with rigid insulation, metal frame wall with batt insulation, slab-on-grade floor with tile and no insulation.
- Windows in the south, east, and west exterior walls, with window areas of 40%, 20%, and 20% of gross wall area, respectively. Glass entrance door, 7'h x 6'w, in the south wall.
- ASHRAE 90.1-2004 minimum prescriptive requirements for thermal performance of walls, roof, door, and glass.

- Maximum occupancy of 67 sq.ft./person, ventilation air at 16 cfm/person.
- 1.5 W/sq.ft. lighting, 1 W/sq.ft. plug loads.
- Occupied schedule Monday-Saturday 10am – 9pm.

The HVAC system used for the baseline RTU in the simulations includes the following:

- Packaged single zone system with direct expansion refrigerant cooling coils and an 81% efficient gas-fired heating section. Seasonal energy efficiency ratio (SEER) of 13 Btu/Wh.
- Dry bulb-based airside economizer section with 65°F high limit and non-integrated economizer (compressor is locked out during economizer operation).
- Fan power from Carrier 48HJ fan performance data: 0.76 BHP for Palm Springs and Sacramento (1,600 cfm @ 0.6” e.s.p.), 1.20 BHP for San Diego (2,000 cfm @ 0.6” e.s.p.). The flow rates were obtained from the simulation outputs for times of peak HVAC cooling load, and the external static pressure of 0.6” matches the average found in installed small rooftop units in California (Jacobs 2003).
- System operates during occupied hours, and for one hour before and after occupied periods.  
Occupied setpoints: 76°F cooling, 70°F heating. Unoccupied setpoints: 82°F cooling, 64°F heating.

The resulting building floor areas and supply airflow rates, based on output from the simulations, are shown in the following table. The building plan dimensions in each climate zone are fixed to match the cooling capacity of a 5-ton baseline RTU.

*Table 5. Building Characteristics*

<b>Location</b>	<b>Building Plan Dimensions</b>	<b>Building Area, sq.ft.</b>	<b>Supply Airflow, cfm</b>	<b>Supply Airflow at Peak Cooling, cfm / ton</b>	<b>Peak Cooling Capacity, sq.ft. / ton</b>
San Diego	60' x 60'	3,600	2,000	390	700
Sacramento	47' x 47'	2,209	1,600	340	470
Palm Springs	43' x 43'	1,849	1,600	350	400

With the building plan dimensions determined, the HVAC system for each building was then modified as follows to include six ARTU features:

- Economizer control was changed from single-point temperature type to differential enthalpy type (Feature 1-03).
- Minimum outside air control method was changed from constant air volume to demand controlled ventilation based on CO<sub>2</sub> differential between building air and outside air (Features 1-04 and 8-04).

- Fan power was reduced to match Carrier 48PG fan performance data: 0.53 BHP for Palm Springs and Sacramento, 0.83 BHP for San Diego (Feature 2-01).
- Unit cooling efficiency was increased from SEER 13 to SEER 14 (Feature 3-01).
- Economizer was changed from non-integrated to integrated so that the economizer can operate simultaneously with the compressor (Feature 7-02).

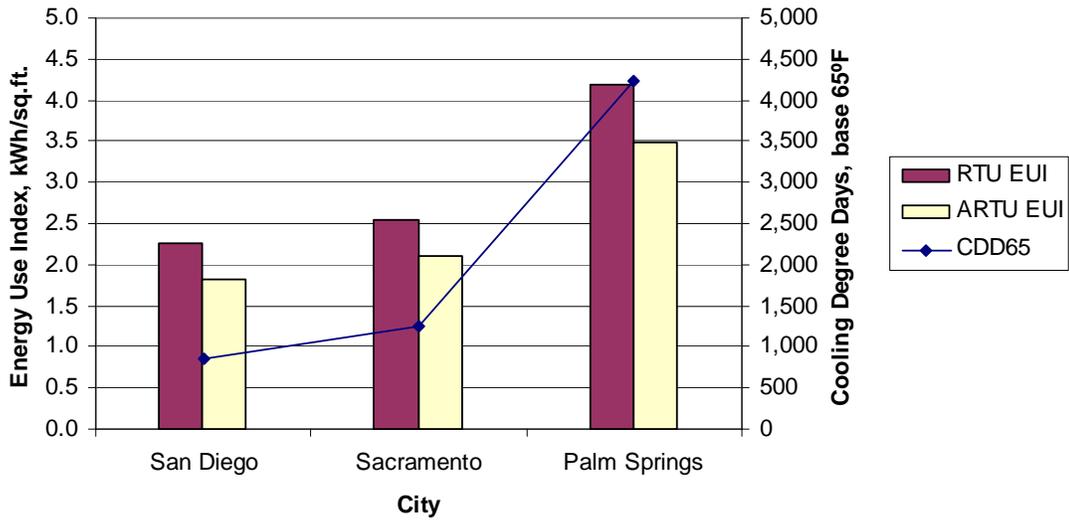
The following table and chart summarize the results of the building simulations for both the baseline RTU and ARTU systems. The difference in annual energy cost between the baseline RTU and ARTU indicated in the following table is included in the benefits summary (Table 3).

*Table 6. Simulation Output*

Location	Electricity*				Natural Gas Heating			
	Annual Usage, kWh		Annual Cost		Annual Usage, kBtu		Annual cost	
	RTU	ARTU	RTU	ARTU	RTU	ARTU	RTU	ARTU
San Diego	8,160	6,540	\$1,080	\$866	524	559	\$5	\$6
Sacramento	5,640	4,660	\$747	\$617	22,560	17,950	\$226	\$180
Palm Springs	7,730	6,460	\$1,023	\$855	4,220	3,020	\$42	\$30
Average	7,177	5,887	<b>\$950</b>	<b>\$779</b>	9,101	7,176	<b>\$91</b>	<b>\$72</b>
Savings	1,290		<b>\$170</b>		1,930		<b>\$20</b>	

\* Consists of HVAC-related electricity use (compressor and supply fan, using approximately 65% and 35% of total annual electricity use, respectively). Does not include electricity use of other building components (lighting and plug loads).

Figure 1. Rooftop Unit (Compressor and Fans) Energy Use Index



Average electricity and natural gas rates (\$0.1324 / kWh, \$10.34 / 1,000 cu.ft.) for California were used in calculating the energy cost savings (EIA 2007).

As a check to verify the validity of the simulation outputs, the following table compares the outputs to average annual electric energy use intensities for existing retail facilities in California (CEC 2006):

Table 7. Annual Electric Energy Use Indices

Building	Cooling and Ventilation, kWh/sq.ft.	Lighting and Plug Loads, kWh/sq.ft.	Total, kWh/sq.ft.
Baseline RTU building*	3.0	8.3	11.3
ARTU building*	2.5	8.3	10.8
Average retail building in CEC study (6,900 sq.ft.)	5.4	7.3	12.7

\* Averaged for the three simulated buildings (one for each city).

As indicated in the table, the lighting and plug loads in the simulation match closely with those from the CEC study. The cooling and ventilation loads are lower for the simulation, most likely due to increases in equipment efficiency.

The energy model was used to evaluate the savings associated with several ARTU features combined together. The remainder of this section includes a detailed discussion of the costs and benefits associated with each individual Operational Performance ARTU feature.

**Feature 1-03:** Economizer control type will be differential dry-bulb, differential enthalpy or dewpoint/dry-bulb temperature control.

Costs: Included in the installed ARTU cost (see Table 2). The baseline RTU includes single-point temperature-based control, and the ARTU includes differential enthalpy-based control.

Benefits: Energy savings due to extended hours of economizer operation. Included in energy use simulation (see Table 6) and the benefits summary (Table 3).

Feature 1-04: Economizer controller will have the capability to operate under demand controlled ventilation (DCV) control.

Costs: Included in the installed ARTU cost (see Table 2). Since the controller for the Carrier 48HJ has the capability to operate under DCV, the savings for removing this feature is included in the deduct from the Carrier 48HJ cost addressed in Table 2.

Benefits: Energy savings due to reduced cooling and heating loads resulting from lowered ventilation rates. Included in energy use simulation (see Table 6) and the benefits summary (Table 3).

Feature 1-05: Compressor operation will be locked out when the outside air temperature is lower than that at which the outside air alone can satisfy the cooling load.

Costs: Included in the installed ARTU cost (see Table 2). The Carrier 48HJ is capable of compressor lockout, but the lockout setpoint for this unit is likely not adjustable.

Benefits: Faster diagnosis of a faulty economizer, in response to comfort complaints. For example, if the lockout is set at 55°F and the economizer isn't working (the system operates at its minimum outside air setting all the time), the space may be too warm at outside air temperatures just under 55°F.

Feature 1-07: Economizer controller will utilize a deadband between economizer enable/disable operation of no greater than 2°F in a dry-bulb temperature application and 2 Btu/lb in an enthalpy application.

Costs: Included in the installed ARTU cost (see Table 2), since the deadband can be set at the ARTU's microprocessor.

Benefits: Energy savings due to extended hours of economizer operation. The energy use simulations for both the baseline RTU and ARTU included an airside economizer with a 65°F dry bulb high limit. To estimate the additional energy use related to an economizer with a 10°F deadband compared to one with a 2°F deadband, the high limit setting was changed to 55°F to model a 10°F deadband and 63°F to model a 2°F deadband. The output from these simulations showed an 8% increase in annual cooling electric energy use with the larger deadband, equating to 320 kWh (\$42). This value is included in the Benefits Summary (Table 3).

Feature 1-09: Outside air and return air dampers will have maximum leakage rates conforming to the requirements of ASHRAE 90.1-2004.

Costs: Included in the installed ARTU cost (see Table 2). The published leakage rates for the dampers on the Carrier 48HJ and 48PG units, given in units of “percent leakage”, do not match the ASHRAE damper leakage criteria (cfm per sq.ft. of damper area). Testing of the 48PG unit found little reduction in damper leakage after applying blade seals.

Benefits: Minimal energy savings. Damper leakage would affect system performance mostly during economizer operation, when the return air damper is 100% closed. Leakage through the return air damper would raise the mixed air temperature, reducing the amount of cooling provided during economizer operation.

Feature 2-01: The ARTU will have supply fan power limitations as addressed in ASHRAE 90.1, when tested according to current ARI rating standards.

Costs: Both the Carrier 48HJ and 48PG comply with ASHRAE 90.1’s fan power limitations for all tabulated external static pressures (0.2” through 2.0”). It is expected that all rooftop units in this size range will comply with 90.1’s fan power limitations as a result of meeting 90.1’s overall unit efficiency requirements (SEER). No cost was added or deducted to the 48HJ and 48PG costs for this feature.

Benefits: Energy savings due to reduced fan energy usage. Included in energy use simulation (see Table 6) and benefits summary (Table 3).

Feature 3-01: ARTU will be Energy Star compliant.

Costs: The current Energy Star eligibility criterion for air-source air conditioners less than 65,000 Btu/h cooling capacity is a SEER greater or equal than 13. Since this is also the minimum efficiency required by ASHRAE 90.1, any unit that complies with ASHRAE is also qualified for Energy Star. While the 48PG is more efficient than the 48HJ (SEER 14 and 13, respectively), no costs were added or deducted to the 48HJ and 48PG costs for this feature.

Benefits: Energy savings due to more efficient cooling. Included in energy use simulation (see Table 6) and benefits summary (Table 3)

Feature 4-01: A high efficiency hydrofluorocarbon (HFC) refrigerant with no ozone depletion potential, such as R-410a, will be used.

Costs: Included in the installed ARTU cost (see Table 2). The Carrier 48HJ uses R-22, and the Carrier 48PG uses R-410a.

Benefits: R-410a has no ozone depletion potential.

Feature 4-02: The condenser fan motor will be a high efficiency PSC type motor.

Costs: The Carrier 48HJ uses a PSC motor. The motor type of the Carrier 48PG could not be verified, but is also expected to be a PSC-type motor. The cost difference between a PSC motor

and a shaded pole motor is expected to be minimal. No costs were added or deducted to the 48HJ and 48PG costs for this feature.

Benefits: PSC motors are more efficient than shaded pole motors. Energy savings related to using a PSC motor would be reflected in the overall unit efficiency (SEER). Included in energy use simulation (see Table 6) and benefits summary (Table 3).

Feature 5-01: Continuous supply fan operation during occupied hours and intermittent operation during unoccupied hours will be the default operating modes.

Costs: Included in the installed ARTU cost (see Table 2). Most commercial-grade thermostats have continuous supply fan operation as a default operating mode, but residential-grade thermostats do not. There is no cost difference between residential- and commercial-grade thermostats.

Benefits: Having continuous supply fan operation as the default operating mode helps ensure compliance with ASHRAE 62 continuous ventilation requirements.

Feature 5-02: During unoccupied hours, supply fan will operate for a short period after compressor turns off.

Costs: Included in the installed ARTU cost (see Table 2). This sequence can be incorporated with the ARTU's microprocessor-based control.

Benefits: Minimal energy savings related to removing the residual energy from the cooling coil.

Feature 6-01: The unit will use an adjustable expansion control device such as a thermostatic expansion valve (TXV) or an electronic expansion valve (EXV).

Costs: Included in the installed ARTU cost (see Table 2). The Carrier 48HJ uses a fixed orifice expansion valve and the Carrier 48PG uses a TXV.

Benefits: A study of installed and operating rooftop units (Jacobs 2003) found that 15% of installed rooftop units are operating with a refrigerant charge that is 5% less than the factory-recommended charge. At this level of undercharge, system cooling efficiency for fixed orifice and thermostatic expansion valves is decreased by 7% and 2%, respectively. The estimated additional annual energy costs related to using a fixed orifice valve instead of a TXV or EXV is \$4. This cost is not included in the benefits summary (Table 3), since this would duplicate the savings claimed under "Diagnostics and Monitoring" (Feature 11-05).

Feature 7-01: A commercial-grade thermostat appropriate for use in commercial buildings will be used.

Costs: Included in the installed ARTU cost (see Table 2). There is no cost difference between residential- and commercial-grade thermostats.

Benefits: Most commercial-grade thermostats are programmable and can sequence multiple stages of cooling (many residential-grade thermostats provide only single-stage capacity control, which could cause comfort issues when used with a multistage rooftop unit).

Feature 7-02: The thermostat or unit controller will incorporate “integrated economizer” control.

Costs: Included in the installed ARTU cost (see Table 2). Since the Carrier 48HJ already incorporates integrated economizer control, the savings for removing this feature is included in the deduct from the Carrier 48HJ cost addressed in Table 2.

Benefits: Energy savings due to extended period of economizer operation. Included in energy use simulation (see Table 6) and the benefits summary (Table 3).

Feature 7-03: Thermostat or controller will be capable of interfacing with an occupancy sensor, switching the unit to intermediate temperature settings when no occupants are present during normally occupied hours.

Costs: Included in the installed ARTU cost (see Table 2). This feature can be incorporated with the ARTU’s microprocessor-based control.

Benefits: The energy use simulations used thermostat setpoints of 76°F and 70°F during occupied hours for cooling and heating, respectively (see discussion in Operational Performance section). Changing these setpoints to 79°F and 67°F, respectively, for one hour per day (12pm-1pm) and rerunning the simulations showed a 1% and 3% reduction in annual electric (cooling) and gas (heating) usage, respectively. This equates to an estimated annual energy savings of 60 kWh (\$8) and 192 kBtu (\$2). These values are included in the Benefits Summary (Table 3).

Feature 8-01: Sensors that are used to detect outdoor air and return air conditions shall have minimum specified accuracies.

Costs: The accuracy of the sensors for the Carrier 48HJ and 48PG units could not be verified. The cost impact for using sensors that meet these accuracies is expected to be minimal.

Benefits: Tighter temperature control, minimal energy savings.

Feature 8-04: If DCV control is to be used, the controller manufacturer will supply a CO<sub>2</sub> sensor that is compatible with the controller, and with terminals that can easily be connected.

Costs: Included in the installed ARTU cost (see Table 2). The CO<sub>2</sub> sensor for the Carrier 48PG is supplied by the controller manufacturer.

Benefits: Greater assurance of sensor-controller compatibility. Energy savings related to DCV control is included in the energy use simulations (see Table 6) and benefits summary (Table 3).

Feature 11-01: Unit controller will utilize an analog to digital resolution no less than 8 bits.

Costs: Included in the installed ARTU cost (see Table 2).

Benefits: Utilizing microprocessor-based control is a prerequisite for many other ARTU features.

### **3.1.2 Maintenance and Serviceability**

In estimating the non-energy savings related to the ARTU features in this sub-group, a service contractor hourly rate of \$90 was used. This rate assumes a union service contractor in California, with a service agreement between the contractor and the building owner.

Based on this rate and the saved service hours indicated in the individual features below, the estimated annual service cost savings related to the ARTU features is \$200. This falls within the range of other estimated FDD-related service savings of \$135 (AEC 2005) and \$540 (Li-Braun 2007).

Feature 9-01: Units with multiple compressors will have labels on the suction, discharge, and liquid lines indicating the appropriate circuit.

Costs: The 5-ton Carrier 48HJ and 48PG units are both single-compressor units, so this feature does not apply. The estimated cost impact for units with multiple compressors is small, on the order of \$50 per compressor.

Benefits: Ease of service, can quickly identify suction, discharge, and liquid lines. Labels make troubleshooting easier and help reduce mix-ups in the field. Estimated annual service cost savings is \$45 per compressor (30 minutes saved service time). This value is not included in the benefits shown in Table 3, since this feature does not apply to single-compressor units.

Feature 9-02: A high-pressure refrigerant port will be located on the liquid line. A low-pressure refrigerant port will be located on the suction line.

Costs: Most rooftop units already have ports on each compressor's suction and discharge line. This feature would move the discharge line port to the liquid line port (downstream of the condenser). There is no expected cost related to making this modification.

Benefits: Improves the ability to troubleshoot. Estimated annual service cost savings is \$90 per year (one hour saved service time). This value is not included in the benefits shown in Table 3, since this would duplicate savings claimed in Features 9-03 and 10-01.

Feature 9-03: When the compressor is located within the condenser fan plenum, pressure ports and adequate refrigerant piping to measure temperature will be accessible from outside of the condenser fan plenum.

Costs: Included in the installed ARTU cost (see Table 2). The ports and piping for the Carrier 48HJ are located inside the condenser fan plenum, while the ports and piping for the Carrier 48PG are located in a separate compartment from the condenser fan plenum.

Benefits: The unit's casing won't be compromised to access the ports and piping. Estimated annual service cost savings is \$90 per year (one hour saved service time). This value is not included in the benefits shown in Table 3, since this would duplicate the savings claimed in Feature 10-01.

Feature 9-04: Controls to adjust the minimum outside air position shall be accessible with air plenum panels in place.

Costs: Included in the installed ARTU cost (see Table 2). Since the minimum outside air damper position for the Carrier 48HJ can be adjusted through its outside air hood without having to remove the air plenum panels, the savings related to removing this feature from the baseline RTU cost is included in the deduct from the Carrier 48HJ cost addressed in Table 2.

Benefits: Saved time during initial air balancing of the unit and whenever adjustments need to be made to the minimum outside air damper position, as the air panels will not have to be removed and reinstalled every time to adjust the minimum damper position potentiometer. Estimated annual service cost savings is \$15 per year (ten minutes saved service time, over the life of the unit). This value is included in the benefits summary (Table 3). Probable energy savings as well, since most outside air dampers are set to deliver more outside air than required.

Feature 10-01: Sensors should be permanently installed to monitor system operation (refrigerant pressures and temperatures, air temperatures and relative humidities), and the controller should have the capability of displaying the value of each parameter.

Costs: Included in the installed ARTU cost (see Table 2). Any sensors not included in the base Carrier 48PG cost are included in the FDD cost.

Benefits: Ease of troubleshooting. Estimated annual service cost savings is \$90 per year (one hour saved service time). This value is included in the benefits summary (Table 3).

Feature 10-02: The controller will provide system status by indicating five operating conditions.

Costs: Included in the installed ARTU cost (see Table 2). The controller for the Carrier 48PG can provide system status for these five operating conditions.

Benefits: Saved time for service technician to determine operating mode of unit. Estimated annual service cost savings is \$45 per year (30 minutes saved service time). This value is included in the benefits summary (Table 3).

Feature 10-03: The unit controller will have the capability to manually initiate each operating mode so that the operation of compressors, economizers, fans, and heating system can be independently tested and verified.

Costs: Included in the installed ARTU cost (see Table 2). The controller for the Carrier 48PG is capable of manually initiating each operating mode.

Benefits: Saved time for service technician to determine operating mode of unit. Estimated annual service cost savings is \$45 per year (30 minutes saved service time). This value is included in the benefits summary (Table 3).

### **3.1.3 Reliability and Robustness**

Most of the features in this sub-group relate to the economizer section. Energy savings estimates are based on energy use simulations, and from information from a previous study (Jacobs 2003) that found that 63% of the economizers on 123 small packaged rooftop units had failed and were not operating.

The base energy use simulations for this report assumed a fully functioning economizer for both the baseline RTU and ARTU (see discussion in Operational Performance section and simulation output in Table 6). Since economizer dampers can fail in either a closed (minimum outside air) or open (100% outside air) position, the economizer section was modified in the ARTU energy use models to include these two scenarios, and the simulations were rerun.

With the outside air damper fixed at a minimum position to mimic a failed closed economizer damper, the simulations showed a 9% increase in annual cooling energy use. Based on 63% of units operating with a failed economizer in this closed position, this equates to a \$29 per year estimated annual energy penalty.

With the unit operating at 100% outside air to mimic a failed open economizer damper, the simulations showed a 20% increase in annual cooling electric energy use and a 432% increase in annual heating gas use. Based on 63% of units operating with a failed economizer in this wide open position, this equates to a \$263 per year estimated annual energy penalty.

These avoided cost values are included in the benefits summary (Table 3).

#### Feature 1-01: Factory-installed economizer.

Costs: Included in the installed ARTU cost (see Table 2).

Benefits: Using a factory-installed economizer helps ensure that it will function properly. The energy savings related to a fully functioning economizer is described above and included in the benefits summary (Table 3).

#### Feature 1-02: Direct drive modulating actuator, gear driven interconnections, and permanently lubricated bushings or bearings on outside air and return air dampers.

Costs: Included in the installed ARTU cost (see Table 2). Since the economizer for the Carrier 48HJ includes this ARTU feature, the savings for removing this feature is included in the deduct from the Carrier 48HJ cost addressed in Table 2.

Benefits: Using a gear driven economizer with a direct drive modulating actuator instead of a linkage-type economizer reduces the possibility of the economizer dampers getting stuck. The

energy savings related to a fully functioning economizer is described above and included in the benefits summary (Table 3).

Feature 1-06: If the discharge air temperature falls below a low limit of 40°F to 45°F (field adjustable), the outside air damper will modulate toward closed until the desired discharge air temperature setpoint is met.

Costs: Included in the installed ARTU cost (see Table 2).

Benefits: Less damper wear due to repeated opening and closing of the damper through its full range whenever the discharge air temperature falls below the low limit. Minimal energy savings.

Feature 1-08: Economizer systems (sensors, dampers, actuators and controller) shall be factory warranted for parts and labor by the manufacturer for 2 to 5 years.

Costs: Included in the installed ARTU cost (see Table 2).

Benefits: Overall improved economizer reliability. The energy savings related to a fully functioning economizer is described above and included in the benefits summary (Table 3).

Feature 8-02: Enthalpy sensors will have solid state electronic humidity sensing elements.

Costs: Included in the installed ARTU cost (see Table 2). Even though the baseline RTU does not use enthalpy sensors and this is reflected in the costs shown in Table 2, it's worth noting that the Carrier 48HJ, if specified with enthalpy-based economizer control, would use solid state enthalpy sensors.

Benefits: More accurate humidity readings, resulting in energy savings due to longer periods of economizer operation.

Feature 8-03: Connectors will be designed to prevent reversed polarity connection at the sensor/controller and actuator/controller connections, or sensors that are not polarity sensitive will be used.

Costs: Included in the installed ARTU cost (see Table 2). Since the Carrier 48HJ already incorporates sensors that are not polarity sensitive, the savings for removing this feature is included in the deduct from the Carrier 48HJ cost addressed in Table 2.

Benefits: Helps ensure a functional economizer. If the economizer is wired incorrectly, the economizer won't function. The energy savings related to a fully functioning economizer is described above and included in the benefits summary (Table 3).

Feature 11-02: Controller will be able to detect faulty and failed sensors (short or open circuit). Upon detecting a faulty sensor, the controller will send a fault signal to the thermostat and/or energy management system. The thermostat and/or energy management system will be capable of receiving and displaying the signal.

Costs: Included in the installed ARTU cost (see Table 2). Some of the items in this feature are included in the Carrier 48PG unit; the rest are included in the FDD package.

Benefits: Faster notification of faulty and failed sensors. Energy savings related to maintaining peak rooftop unit operating efficiency by replacing faulty sensors.

Feature 11-03: Sense a non-operating or improperly operating economizer damper and send a fault signal upon detection.

Costs: Included in the installed ARTU cost (see Table 2). The Carrier 48PG unit includes this feature.

Benefits: Faster notification of economizer damper faults. The energy savings related to a fully functioning economizer is described above and included in the benefits summary (Table 3).

### **3.2 Diagnostics and Monitoring**

Feature 11-04: The unit will have the diagnostic capability to detect when the temperature differential across the evaporator coil is less or greater than a predetermined value (i.e. target temperature drop as determined by Carrier Slide Rule or equivalent calculator).

Costs: Included in the installed ARTU cost (see Table 2). Part of this feature is included in the Carrier 48PG unit; the rest is included in the FDD package.

Benefits: A previous study (Jacobs 2003) found that 39% of 79 small rooftop units in operation were supplying air at less than 300 cfm/ton, the average supply airflow rate was 325 cfm/ton, and the average additional energy use related to this low supply airflow is 9% of the annual cooling energy.

The average annual cooling energy of the modeled ARTU, from the energy use simulations (see discussion in the Operational Performance section), is 4,027 kWh. Assuming that 39% of units are operating at a supply airflow rate that increases annual cooling energy use by 9%, the estimated annual avoided energy cost for this feature is \$19. This value is included in the benefits summary (Table 3).

Feature 11-05: The unit will have the diagnostic capability to self-monitor refrigerant charge level, and detect when the refrigerant charge is outside preset limits.

Costs: Included in the installed ARTU cost (see Table 2). Part of this feature is included in the Carrier 48PG unit, the rest is included in the FDD package.

Benefits: A previous study (Jacobs 2003) found that 46% of 74 small packaged rooftop units in operation had an improper refrigerant charge. The average increased cooling energy use for the units with improper refrigerant charge was estimated at 5%.

The average annual cooling energy of the modeled ARTU, from the energy use simulations (see discussion in the Operational Performance section), is 4,027 kWh. The estimated avoided annual energy cost related to improper refrigerant charge, based on 46% of units using 5% more cooling energy per year, is \$12. This value is included in the benefits summary (Table 3).

In addition, this FDD feature will reduce time required by the service technician to determine the amount of charge adjustment needed improve system operation. Based on a previous study regarding economic benefits associated with FDD features (Li-Braun 2007), the non-energy benefits associated with this measure has been estimated at \$44. This value is included in the benefits summary (Table 3).

Feature 11-06: The ARTU controller will be able to diagnose and send a fault signal for severe and degradation faults.

Costs: Included in the installed ARTU cost (see Table 2). Part of this feature is included in the Carrier 48PG unit; the rest is included in the FDD package.

Benefits: Faster notification of degraded unit efficiency or catastrophic failure. In addition, this FDD feature will reduce time required by the service technician to troubleshoot system operational problems and implement necessary repairs. Based on a previous study regarding economic benefits associated with FDD features (Li-Braun 2007), the non-energy benefits associated with this measure has been estimated at \$56. This value is included in the benefits summary (Table 3).

## 4.0 Conclusions

This report presents the costs and benefits related to 36 advanced rooftop unit features. An attractive aspect of these features is that over half of them are currently available on higher-end commercial rooftop units. The costs and benefits in this report are for a 5-ton rooftop unit, since that is one of the most common sizes found in small commercial applications.

The cost information contained in this report is based on actual costs for currently available equipment. Benefit estimates were made using information from previously published reports, energy modeling software, and service estimates.

As indicated in the report, the estimated cost for incorporating the ARTU features in a basic 5-ton rooftop unit is \$4,100. The annual combined energy and non-energy benefit related to the ARTU features is between \$600 and \$830. This gives a simple payback time of between 4.9 and 6.8 years.

Besides the actual cost of the ARTU features, production quantities could also be a factor in the cost difference. The number of “ARTU”s sold in the U.S. is currently only 5% of the number of basic rooftop units sold. This large production difference could also be influencing the cost difference between a RTU and an ARTU.

The \$230 benefit range is due to the unknown position of failed economizer dampers. To reduce this range, the position of failed economizers must be known. If all failed economizers have failed in a closed position, the annual benefit related to incorporating ARTU features that will ensure a functional economizer (or, the energy penalty related to a failed closed economizer) is \$30; if they fail in a fully open position, the benefit is \$260.

Many of the ARTU features relate to serviceability and reliability, not just base energy efficiency. As shown in this report, energy use increases when field-installed economizers are incorrectly installed, when economizers are wired backwards, and when the unit is operating with a refrigerant charge that is outside preset limits. While none of these relate to the published ARI unit efficiency, they have an impact on energy use.

Commercially available rooftop units that include most of the ARTU features are popular in owner-occupied buildings. The building owners appreciate the robustness of these units, and recognize the value of the additional diagnostics and ease of maintenance.

## 5.0 References

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