FIELD PERFORMANCE ASSESSMENT OF PACKAGE HVAC EQUIPMENT TO QUANTIFY BENEFITS OF PROPER SERVICE

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Abstract

This paper presents the results of using data collected through two field monitoring studies to address the issue of quantifying the effects from diagnosing and servicing faults in commercial and residential packaged HVAC units. For these studies, a set of open source, non-proprietary field measurement and diagnostic procedures were developed and used for making measurements to diagnose and detect faults in the operation of commercial and residential HVAC units. For 35 commercial HVAC units that were diagnosed and serviced, the average EER increased from 7.37 before servicing to 7.92 after servicing, an increase of about 7.4%. This change was statistically significant at a 95% confidence level. For 43 residential HVAC units that were diagnosed and serviced, the average EER increased from 6.64 before servicing to 7.05 after servicing, an increase of about 6.1%. However, this change was statistically significant only at a confidence level of 80%.

Introduction and Overview

Because the installed stock of packaged HVAC equipment is large, improvements in the performance of that equipment can have significant impacts on HVAC energy use. For example, the *California Energy Efficiency Potential Study* (May 2006) estimated the total technical potential for kWh savings from HVAC measures to be about 3.285 GWh for the residential sector and about 3.121 GWh for the commercial sector. HVAC diagnostics and tune ups account for about 16% of the residential potential and about 43% of the commercial potential.

Various methods, protocols, and tools for detecting and diagnosing faults in residential and commercial packaged HVAC units are in use in the market. However, there are questions both about the performance of the methods and about the savings that are achieved when the faults diagnosed with the methods are corrected.

Many of the existing protocols for detecting and diagnosing HVAC faults are proprietary. In the studies reported on here, open source, non-proprietary protocols for detecting and analyzing the effects of HVAC equipment servicing were developed and applied. A common set of field measurement procedures was developed specifically for these projects and used to collect data with which to assess the performance of packaged HVAC equipment.

The results of applying these procedures and assessing the changes in performance for serviced HVAC units are presented in this paper. Results are reported for two projects, with one project involving commercial units and the other residential units.

Field Measurement Procedures

Field measurement procedures were developed specifically for this project. Techniques were developed for taking measurements in the field; appropriate field data collection forms and electronic spreadsheets that could be used in the field were also developed.

In practice, these procedures evolved to their final form through an interactive process between the study team and project advisors. The contractor staff prepared and tested an initial set of field procedures. Based on an analysis of results from this preliminary field testing, a final set of procedures were developed. Table 1 presents the list of points for which measurements were to be taken on each unit.

Table 1. Measurement Points

Point	***Abbreviation***	***Description***
1	kW_{Total}	Total electric Power to the unit, kW
2	SA_{cfm}	Supply Air flow rate computed as measured average air speed in duct multiplied by duct cross-sectional area (width x height), cfm
3	SAT_{db}	Supply Air Temperature, dry-bulb, °F
4	SA_{rh}	Supply Air relative humidity, %
5	SA_{sp}	Supply Air duct static pressure, in. H_2O
6	MAT_{db}	Mixed Air Temperature, dry-bulb, °F
7	MA_{rh}	Mixed Air relative humidity, %
8	OAT	Outside Air Temperature (ambient dry-bulb), °F
9	OA_{rh}	Outside Air relative humidity (ambient), %
10	CA	Condenser Air or Air Off the Condenser Temperature, °F
11	SP	Refrigerant Suction line pressure, psig
12	LP / DP	Refrigerant Liquid Line or Discharge line pressure, psig
13	ST	Refrigerant Suction line Temperature, °F
14	LT	Refrigerant Liquid line Temperature, °F

To ensure comparability of performance measurements across units, the protocols also specified the conditions under which the performance measurements were to be taken.

- The unit had to be in full load operation and at steady state during the performance tests. Ambient temperature had to be more than 75°F, and the unit had to have been running for 10-15 minutes or longer to ensure steady state conditions.
- If the unit being tested had multi-stage compressors, checks were to be made to ensure that all stages of the compressor were in use. However, if the compressors had separate refrigerant circuits, one stage was considered sufficient for the testing.
- If the unit was a heat pump, it had to be operating in a cooling cycle.
- All access panels had to be in place.
- Low ambient temperature controls had to be disabled or turned off during the testing.
- All outside air intakes for the units had to be sealed, so that the units were running on 100% return air during the measurements. In effect, this meant that the return and mixed air properties and flows would be the same. The designated location for measurements of the warm air was in the mixed air chamber. However, if access to the mixed air chamber was obstructed, measurements could be taken in the return air duct. Similarly, if the airflow measurements could not be made in the supply air duct, they could be taken in the return air duct.
- Sensors and meters had to be prepared and placed such that all measurements (except air flow) could be read and recorded as quickly as possible. The meter values were to be recorded on the data collection form. The airflow measurements were to be made immediately following all other data collection.

Table 2 shows the equipment used for the taking the performance testing measurements. All test equipment were calibrated according to manufacturer's recommendations. All equipment was checked periodically to ensure proper operation and that calibration was within field testable conditions.

Table 2. Types of Measurement Equipment and What Measured

Type of Equipment	***What Measured***
Thermo-anenometer	Airflow, relative humidity, temperature
Sper Scientific Model 80027 relative humidity / temperature monitors with remote sensors	Duct, ambient and condenser air relative humidity and temperature
Raytek MiniTemp FS infrared thermometer	Refrigerant liquid line temperatures
AEMC 3910 Power Meter	True RMS voltage, current, power and power factor
Fluke 33 True RMS Clamp-on ammeter	Used to compare calibration of current reading of power meter
Ritchie Model 41232 Refrigerant Manifold Gauges	Pressure within either high side or low side of refrigeration system

Diagnostic Testing Procedures

For the diagnostic testing, baseline measurements were first made on the sampled units and diagnostic testing procedures were then used to identify units for which refrigerant charging or other servicing was needed.

In practice, servicing of an HVAC unit is based on a hierarchy of fault detection. A guideline for servicing of faults is provided in Table 3.

Table 3. Hierarchy of Servicing Faults

Item	**Fault Type**
1	Incorrect Supply fan air flow across evaporator coil.
2	Non-condensibles in refrigerant line.
3	Condenser fouling.
4	Expansion device and liquid line restrictions.
5	Refrigerant charge incorrect.
6	Miscellaneous – tighten fan belt, mounting bolts, clean and drain condensate pan and line.

Consistent with diagnosis results, servicing begins with Item 1 in Table 3. The diagnostic procedures for detecting faults are based on the presumption that there is proper air flow across the coil. Therefore, for determining what servicing was required, air flow is measured and tested first. Air flow rates must be established and certified as within the nominal operation, as a prerequisite for refrigerant side diagnostics. Examples of criteria used to determine whether air flow is sufficient include the following.

- The airflow rate should be within the nominal range of 320-480 CFM per ton (or whatever range is specified as nominal by the manufacturer) before a next level of diagnostics can be applied.
- If the calculated total heat capacities are significantly below the rated capacity of the unit, it is an indication that the unit is delivering considerably more air across the evaporator coil

than is designed or expected, in CFM per ton of cooling capacity. This could mean that the ductwork system is leaking air.

- If the calculated total heat capacity is significantly greater than the rated capacity of the unit, it is an indication that the unit is delivering considerably less air across the evaporator coil than designed/expected.
- If the economizer damper fails to operate during any of the tests, the unit is diagnosed as needing service.

If measurements and testing show that there are problems with the air flow, those problems are fixed before further measurements were made. After faults causing improper air flow have been serviced, the unit is retested and another full set of measurements is made. Using the test data, several different parameters are calculated that are used in qualitatively diagnosing the operating condition of the? unit. These parameters are defined in Table 4.

Table 4. Definitions of Parameters Used for Fault Diagnostics

Abbreviation	Definition
ET	Evaporator temperature, measured as T_{sat} at low side pressure
SC	Sub-cooling, condenser saturation temperature at high-side subtracted by liquid line temperature
SH	Super heat
ETD	Temperature drop across evaporator
CTD	Air Temperature Increase over Condenser Coils, calculated by subtracting ambient dry-bulb temperature from condensing temperature (CT)
COA	Condenser over air temperature, CT minus ambient

The values for the parameters in Table 4 are calculated using the following equations and procedures:

ET: Lookup temperature based on suction pressure from property table
$SC = CT - LT$
$SH = ST - ET$
$ETD = MAT_{db} - SAT_{db}$
$CTD = CA - OAT$
$COA = CT - OAT$

Values for the parameters ET, SC, SH and COA are determined for each stage of a unit. Values for the parameters ETD and CTD are determined for a unit independent of the number of stages.

Value ranges for the parameters defined in Table 4 were specified and used to qualitatively diagnose the current operating condition of the unit. These ranges are shown in Table 5.

Table 5. Ranges for Proper A/C Operation

Parameter	*Standard Efficiency Units*		*High Efficiency Units (SEER ≥ 12)*	
	Target	*Normal Operation Range*	*Target*	*Normal Operation Range*
ET	40	30 - 50	43	33 - 50
SC	15	8 – 20	10	3 – 15
SH	20*[1]	-10/+10 of target value and minimum is 5 F	20*[1]	–10/+10 of target value and minimum is 5 F
ETD	20	15 – 30	25	20 – 40
CTD	20	10 – 30	15	5 – 25

COA	20	10 – 30	15	5 – 25
CFM/ton	400	320 – 480	400	320 – 480

[1] For TxV unit, target value is 20; for non TxV unit derive from tabulated values .

The values that were calculated for the parameters ET, SC, SH, COA, ETD and CTD are used to qualitatively diagnose common operational faults for HVAC units (e.g., refrigerant under or over charge, compressor valve leak, liquid-line restriction, condenser fouling and evaporator fouling problems). Other than air flow, most of the diagnostic faults are independent of each other.

These measurements are used to determine whether the unit needs a refrigerant charge adjustment (i.e., item 5 in Table 3 is checked). After a charge adjustment is made, the unit is again retested and another full set of measurements made. If necessary, servicing is performed for item 6 (although this item is not part of measurement diagnostic procedures).

Table 6 shows the matrix used for preparing the diagnosis. For an example, evaporator coil fouling causes ET to drop, measured SH (SH_m) to drop, ETD to go up, while the other three parameters remained normal. Consequently, this combination of values for the six parameters means that the unit has fouled evaporator coils that need cleaning.

Table 6. Operational Fault Detection and Diagnostics Matrix

Fault	***Type***	***ET***	***SH_m***	***CTD***	***SC_m***	***COA***	***ETD***
Inefficient Compressor	All	⇑*					
Condenser coil fouling	All			⇑	- /⇓	⇑	
Evaporator coil fouling	All	⇓	⇓				-/⇑
Refrigerant –Low charge	TXV	⇓			⇓	- /⇓	
Refrigerant –Low charge	nTXV	⇓	⇑		- /⇓		
Refrigerant – High Charge	TXV	- /⇑	- /⇓		⇑		
Refrigerant – High Charge	nTXV	- /⇑	⇓				
Refrigerant – Non condensables	All			- /⇓	- /⇑	⇑	
Liquid-line restriction	All	⇓	⇑		⇑		

Symbols:
⇑ = parameter higher than normal range,
⇓ = parameter lower than normal range,
⇑* = High range starts 15° above ET target value.

The procedure for verifying the proper refrigerant charge for a unit depends on whether the unit does or does not have a Thermal Expansion Valve (designated with (TXV) and (nTXV), respectively).

For units without a thermal expansion valve flow device (nTXV), measurements of return air wet bulb temperature (RATwb), outdoor air dry bulb temperature (OATdb), suction line pressure (SP), suction line temperature (ST), evaporator saturation temperature (ET) (which is the saturation temperature at the pressure SP) are used to determine the charge condition as follows:

- Use RATwb and OATdb parameters and look-up table to determine the required superheat (SHr).
- Calculate Actual Superheat (SHm) = ST – ET
- Calculate Superheat difference (SHd) = Actual super heat SHm – Required superheat SHr

Then, the charge condition for units without a thermal expansion valve is determined using the following logic:

5 ≥ SHd ≥ -5 → Do nothing. Charge is within acceptable limits.
SHd > 5 → Add charge
SHd < -5 → Remove charge

For units with a thermal expansion valve flow device (TXV), the sub-cooling method is used to determine the charge levels. A high-efficiency unit is expected to maintain the required sub-cooling (SCr) at 15°F and a standard efficiency unit at 10°F. Using the high-side pressure (LP) measurement and the measured liquid line temperature (LT), the measured sub-cooling is determined as follows.

- For a given refrigerant, the Condenser Saturation Temperature (CT) is the saturation temperature at the high-side pressure (LP).
- Measured sub-cooling = CT – LT
- Sub-cooling difference (SCd) = Measured sub-cooling SCm – Required sub-cooling SCr

The charge determination logic for a unit with a thermal expansion valve is as follows:

$3 \geq SCd \geq -3$ → Do nothing. Charge is within acceptable limits.
$SCd > 3$ → Remove Charge
$SCd < -3$ → Add charge

Those units that need removal or addition of charge are charged according to the nameplate specification for refrigerant charge. The amount of refrigerant charge adjustment (either removal or addition) is weighed and recorded.

Results from Study of Commercial Packaged HVAC Units

The field measurement and diagnostic procedures were applied in a study of commercial packaged HVAC units. In this study, field measurements were taken and diagnostics performed for 184 commercial packaged HVAC units distributed across five cities throughout the United States. Sites selected for the study were located in five cities, with each city representing a unique climate condition. The five selected cities wre:

- Houston, Texas, a hot and humid climate.
- Baltimore, Maryland, a mixed-humid climate.
- Sacramento, California, a hot and dry climate.
- Los Angeles, California, a mixed-dry climate
- Chicago, Illinois, a cold climate.

Table 7 shows the planned and achieved distributions for the sample of commercial HVAC packaged units in the selected cities.

Table 7. Distribution of Commercial HVAC Units Selected for Baseline Measurements and Servicing: Proposed and Achieved, by City

City	***Proposed***			***Achieved***		
	Baseline Only	***Baseline & Servicing***	***Total***	***Baseline Only***	***Baseline & Servicing***	***Total***
Sacramento	30	11	41	33	6	39
Los Angeles	31	10	41	25	0	25
Chicago	31	10	41	29	11	40
Houston	31	10	41	33	7	40
Baltimore	30	10	40	29	11	40
Total	153	51	204	149	35	184

HVAC units were selected to cover different size and age categories. The distribution of the 184 units by size, age and type of compressor is shown in Table 8.

Table 8. Distribution of Commercial Study HVAC Units by Size, Age and Type of Compressor

Size Group	***Age Group***	***Type of Compressor***		***Totals***
		Reciprocal	***Scroll***	
Under 10 Tons	***Under 10 Years***	3	61	64
Under 10 Tons	***10 Years or more***	34	8	42
10 Tons or More	***Under 10 Years***	6	16	22
10 Tons or More	***10 Years or more***	44	12	56
Totals		87	97	184

Of the 184 units, 49 units were high-efficiency units. There were 65 units that did not have thermal expansion valves and 115 that did.

Data were collected through field measurements using the procedures described above and used to calculate values for the parameters ET, SC, SH, COA, ETD and CTD. These parameter values were then used to qualitatively diagnose operational faults for the units. Table 9 reports the numbers of different types of faults that were determined for the different stages of the units tested. Table 10 reports the number of units with different numbers of faults for the individual stages tested and for all units tested. Out of the 184 units tested, 76 units had no faults when both Stage 1 and Stage 2 tests are considered, 62 units had one fault, 40 units had two faults, and 6 units had three faults.

Table 9. Results of Fault Diagnostic Testing for Commercial HVAC Units

Type of Fault	***Stage 1***	***Stage 2***
Inefficient Compressor?		
No	182	81
Yes	2	1
Refrigerant Flow Restriction?		
No	184	82
Yes	0	0
Condenser Fouling?		
No	184	80
Yes	0	2
Evaporator Fouling?		
No	181	82
Yes	3	0
Charge Problem?		
No Charge Fault	107	38
High Charge	56	28
Low Charge	12	6
Non-condensable	9	10
Air Flow?		
Normal	153	
High CFM	29	
Low CFM	2	
Totals	184	82

Table 10. Numbers of Faults Detected for Commercial HVAC Units Tested, by Stage and Overall

Number of Faults	*Units with Faults in Stage 1*	*Units with Faults in Stage 2*	*Units with Faults in Either Stage*
0	90	36	76
1	75	45	62
2	19	1	40
3	0	0	6
Total Number of Units	184	82	184

Servicing to correct faults was performed for 35 units. The distribution of the units for which performance testing was applied is shown in Table 11.

Table 11. Distribution of Commercial HVAC Units Receiving Baseline Measurements and Servicing, by City

City	*Baseline Only*	*Baseline & Servicing*	*Total*
Sacramento	33	6	39
Los Angeles	25	0	25
Chicago	29	11	40
Houston	33	7	40
Baltimore	29	11	40
Total	149	35	184

The pre- and post-servicing measurements for the 35 units were used to calculate the EERs for the units at standard conditions before and after the servicing. The average EER for the units increased from 7.37 before servicing to 7.92 after servicing, an increase of about 7.4%. The results of a paired t-test (reported in Table 12) showed that the hypothesis of no difference between the pre- and post-servicing averages can be rejected with a confidence level of 95%.

Table 12. Results of Paired t-test on Commercial HVAC Units with EERs Calculated from Pre- and Post-Servicing Data

	Pre-Servicing EER	*Post-Servicing EER*
Mean	7.37	7.92
Standard Deviation	2.49	1.95
Observations	35	
Pearson Correlation	0.86	
Hypothesized Mean Difference	0	
Degrees of freedom	34	
t Stat	- 2.47	
P(T<=t) two-tail	0.02	

Table 13 shows the changes in EER for the serviced commercial HVAC units when the units are classified by the number of faults detected during the diagnosis.

Table 13. Changes in EERs for Commercial HVAC Units by Number of Faults Detected

Number of Faults Detected	***Number of Units***	***Pre-Servicing EER***		***Post-Servicing EER***	
		Mean	***Standard Deviation***	***Mean***	***Standard Deviation***
None	3	10.66	1.23	10.51	2.84
One	19	6.63	1.84	7.29	1.17
Two	13	7.69	2.93	8.23	2.23
All Units	35	7.37	2.49	7.92	1.95

The data for the 35 units were further examined to see if the changes in EERs from before to after servicing were related to such factors as the sizes of the units, their ages, or the locations of the units. This examination showed no strong relationships between the changes in the EERs and the sizes or ages of the units or the cities where the units were located.

Results from Study of Residential Packaged HVAC Units

In a second study, the field measurement and diagnostic procedures were used to assess the effects of maintenance and tune-up servicing of residential packaged HVAC units. A sample of residential air conditioning units for this study was selected from among households who had participated in a utility demand response program. The pool from which to recruit households for the field testing and measurements included 148 households, with a total of 168 air conditioning units. Letters explaining the testing project were sent to all 148 households. Follow-up telephone calls were then made to the households to recruit them for the project. The result of this recruiting effort was that 106 households with 120 air conditioning units agreed to participate in the testing project. The distribution of the 120 units by size, age and type of compressor is shown in Table 14.

Table 14. Distribution of Sample Residential HVAC Units by Size, Age and Type of Compressor

Size Group	***Age Group***	***Type of Compressor***		***Totals***
		Reciprocal	***Scroll***	
Under 4 Tons	***10 Years or Less***	15	10	25
Under 4 Tons	***More than 10 Years***	23	5	28
4 Tons or More	***10 Years or Less***	9	21	30
4 Tons or More	***More than 10 Years***	29	8	37
Totals		76	44	120

Of the 120 units tested, 31 units were high-efficiency.

Data were collected through field measurements using the procedures described above and used to calculate values for the parameters ET, SC, SH, COA, ETD and CTD. These parameter values were then used to qualitatively diagnose operational faults for the units. Table 15 reports the numbers of different types of faults that were determined for the residential HVAC units tested. Of the units tested, 72% had no or one fault. Only 28 % of the baseline units had more than one fault identified; for all of those units one of the faults was with the air flow.

Table 15. Results of Fault Diagnostic Testing for Residential HVAC Units (Total n = 109)

Type of Fault	***Number of Units with Fault***
Inefficient Compressor?	4
Refrigerant Flow Restriction?	4
Condenser Fouling?	0
Evaporator Fouling?	2
Charge Problem?	
High Charge	30
Low Charge	6
Non-condensable	12
Airflow?	
High CFM	2
Low CFM	59
Total number of units diagnosed	109

Table 16 reports the numbers of units with different numbers of faults. Of the 109 units for which diagnoses of faults were made, 89 were diagnosed with at least one fault. This table also presents average standardized EER values for units tested by number of faults.

Table 16. Numbers of Faults Detected and Average Standardized EER for Residential HVAC Units Tested

Number of Faults	***Number of Units with Faults***	***EER under Standard Conditions***	
		Average	***Standard Deviation***
None	20	8.20	2.48
One	58	6.45	2.15
Two	27	5.81	2.38
Three	4	4.35	3.20
Total # of Units	109	6.54	2.45

Of the residential HVAC units tested, there were 43 that received refrigerant charge servicing from an HVAC contractor and for which pre-servicing and post-servicing measurements were made. These measurements provide data for assessing changes in the performance of the units.

The pre- and post-servicing measurements were first used to analyze changes in the EERs for the units at standard conditions before and after the servicing. The average EER for the units increased from 6.64 before servicing to 7.05 after servicing, an increase of about 6.1%. However, the results of a paired t-test (reported in Table 17) show that the hypothesis of no difference between the pre- and post-servicing averages can be rejected only with a confidence level of 80%.

Table 17. Results of Paired t-test on Residential HVAC Units with EER Calculated from Before- and After -Servicing Data

	Before-Servicing EER	***After-Servicing EER***
Mean	6.64	7.05
Standard Deviation	2.13	2.87
Observations	43	
Pearson Correlation	0.72	
Hypothesized Mean Difference	0.00	
Degrees of freedom	42	
t Stat	-1.341	
P(T<=t) two-tail	0.187	

Table 18 shows the changes in EER for the serviced residential HVAC units when the units are classified by the number of faults detected during the diagnosis.

Table 18. Changes in EERs for Residential HVAC Units by Number of Faults Detected

Number of Faults Detected	***Number of Units***	***Pre-Servicing EER***		***Post-Servicing EER***	
		Mean	***Standard Deviation***	***Mean***	***Standard Deviation***
None	8	8.23	2.23	9.36	3.80
One	26	6.31	2.12	6.35	2.24
Two	9	6.18	1.50	7.01	2.82
All Units	43	6.64	2.13	7.05	2.87

Conclusions

For the studies reported on in this paper, a set of open source, non-proprietary field measurement and diagnostic procedures were developed. These procedures were used in two studies for making measurements to diagnose and detect faults in the operation of commercial and residential HVAC units. Baseline measurements were made on all sample units, with servicing provided for units for which defaults were detected. These units were re-tested after the servicing. Paired pre- and post-servicing values for EER measured at standard conditions were used to determine how the average EER for serviced units changed as a result of the servicing.

- For 35 commercial HVAC units that were serviced, the average EER increased from 7.37 before servicing to 7.92 after servicing, an increase of about 7.4%. This change was statistically significant at a 95% confidence level. Further examination indicated that there were no strong relationship between the percentage changes in the EERs and either the sizes or the ages of the units.
- For 43 residential HVAC units that were serviced, the average EER increased from 6.64 before servicing to 7.05 after servicing, an increase of about 6.1%. However, this change was statistically significant only at a confidence level of 80%.

The results of these studies are intended to contribute to better quantifying the savings from correcting faults diagnosed in residential and commercial packaged HVAC units. They can contribute to developing deemed savings associated with measures used to improve the performance of existing HVAC units.

There are some areas where further research on diagnostic testing of the performance of HVAC units could be conducted.

- The sensitivity of the measurement points should be evaluated prior to selection of the field measurement protocols in order to minimize field measurement points.
- Due to the turbulent environment in the ducting of packaged rooftop units, the measurement of airflow is an area that could benefit from additional research.
- After a set of protocols with consistent and repeatable results under a single set of conditions has been developed, these must be tested under varying conditions in order to refine the normalization of EER to standard conditions. Whether or not the EER normalization factor is consistent across unit types should also be assessed.

These efforts would provide more refined diagnostic procedures for application to future studies of the effects of servicing on the performance of commercial and residential HVAC units.